Diamond Lake Database 2001

Prepared for the
Umpqua National Forest
Roseburg, Oregon

By

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ABSTRACT

Diamond Lake experienced a severe bloom of *Anabaena flos-aquae* in summer 2001. The abundance of the cyanobacteria and the toxins produced by the cyanobacteria prompted the Umpqua National Forest to close the lake to contact for a period in August. A number of different organizations were mobilized to collect data on the lake in addition to the planned sampling programs. The purpose of this report is to summarize the data collected on Diamond Lake and supplemental data that may be useful to interpret the cause(s) of the bloom. The data were obtained from a number of organizations, reviewed, and entered into an Access© database developed for this project.

The data review identified a number of opportunities for improving the data collection, analytical preparation, and data processing. Areas of particular focus included the need to standardize the collection of water quality profile data, the need to adjust the suite of parameters being monitored, and the desirability of integrating existing climate collection on the Forest to better meet the needs of the analysis of lake processes.

The analysis of the data indicated that inorganic phosphorus, nitrogen and silica discharged to the lake are assimilated rapidly in the lake resulting in a net loss of phosphorus and silica to the sediments and a net export of organic nitrogen to the downstream waters through Lake Creek. The high primary production in the lake caused water quality standards for pH to be exceeded for much of the summer, with a maximum pH of 9.2 measured. Dissolved oxygen was depleted in the hypolimnion during July and August when stratification occurred. Dissolved oxygen concentrations were below saturation values in the surface waters during the height of the bloom. The bloom conditions were notable for transforming the color of the lake to an aquamarine appearance. Secchi disk transparency decreased to a minimum of 0.25 m and chlorophyll a concentrations exceeded 60 ug/L.

The phytoplankton assemblage was dominated by *Anabaena flos-aquae* in July and early August and at some points represented 98% for the biovolume of the phytoplankton. The cyanobacteria were in sufficient abundance (toxigenic *Anabaena*) to exceed WHO guidelines for contact. A secondary bloom of *Fragilaria crotonensis*, a planktonic diatom, appeared that would have been significant had it not been largely masked by the cyanobacteria. Despite the severity of the bloom, no loss of fish life was noted, although the reduction of transparency for an extended period of time appeared to contribute to die-off and uprooting of substantial amounts of macrophytes.

INTRODUCTION

Diamond Lake is a natural lake located in the Umpqua National Forest north of Crater Lake National Park. The features of the lake are described in Table 1.

Attribute	Metric	English
Elevation	1580 m	5183 ft
Lake Area	1301 ha	3214 ac
Watershed Area	136 km^2	55 mi^2
Maximum Depth	15.8 m	52 ft
Mean Depth	7.3 m	24 ft
Volume	95.11 hm^3	77,100 ac-ft
Retention Time	1.6 yr	
Latitude/Longitude	43 11 02 d/m/s	122 09 57
Precipitation	140-165 cm	55-65 in

Source: Johnson et al. 1985

The general features of the lake and watershed are presented in Figure 1. There are two permanent inlets to the lake, Silent Creek and Short Creek or which the vast majority of discharge is derived from Silent Creek. Water exits Diamond Lake from Lake Creek. Lake stage in Diamond Lake is regulated during the summer months by a weir located at the outlet. The lakeshore has been developed for recreation to include several hundred campsites operated by the Umpqua National Forest (UNF). The UNF has also provided for private development through lease of land on the southwestern shore for private seasonal residences, a RV park on the southeastern shore, and a resort on the northeastern shore. Wastewater from the campgrounds and resort are collected and treated in lagoons outside of the watershed.

Prior to 1910, Diamond Lake was fishless. The Oregon Game Commission [OGC] (now the Oregon Department of Fish and Wildlife[ODFW]) introduced trout to the lake. A very successful sport fishery existed until the 1940's when a decline became evident. The decline in the trout fisheries was attributed to the unsanctioned introduction of Tui chub from the Klamath Basin. Diamond Lake was treated with rotenone by the OGC in 1954 and rainbow trout were reintroduced in 1955. The trout fishery was once again very successful until the early 1990's when Tui chub were found to be present. The trout fisheries survives now only through the stocking of large fish. The fisheries biomass is now totally dominated by Tui chub.

Diamond Lake has been a productive lake, which has contributed to the previous successful trout fishery. However, there is evidence that the water quality in the lake has deteriorated, possibly in response to the changes in fisheries (Eilers et. 2001a,b). In addition to the inferences derived from the paleolimnology, the zooplankton population has experienced a loss of larger cladocerans over the last decade (A. Vogel, pers.comm, 2001).

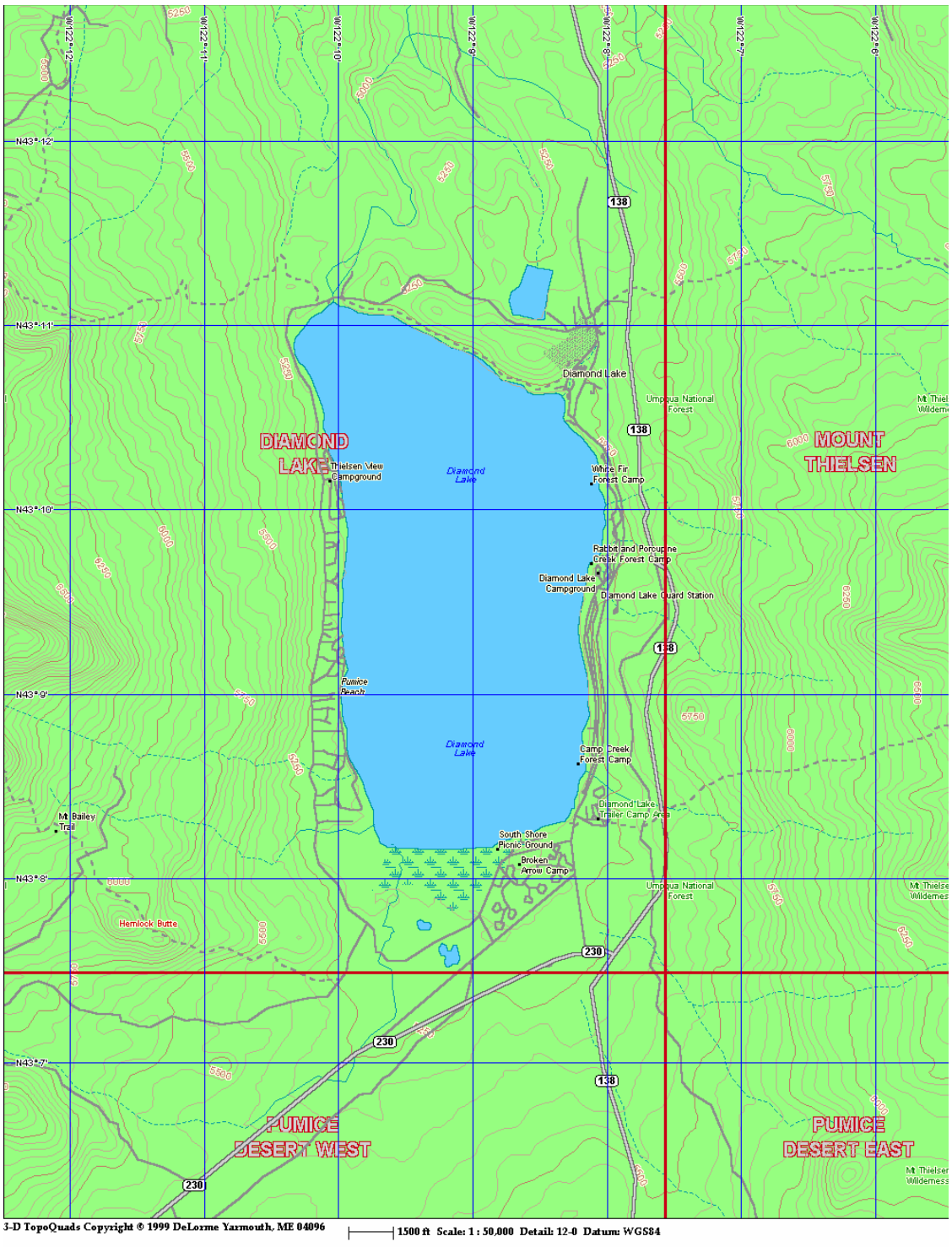

Figure 1. Diamond Lake, Oregon

Figure 1. Diamond Lake, Oregon (Approx. scale 1:50,000).

In July 2001, a major phytoplankton bloom developed on Diamond Lake. ODFW personnel notified DEQ of the bloom on July 11 and a sample was collected from the lake outlet on July 25. The results of that sample, which indicated 98% of the phytoplankton biovolume was *Anabaena flos-aquae*, were made available to the Forest Service on July 27. Those results prompted to Forest Service to initiate additional lake sampling for August and September to supplement existing work being conducted on the lake by the Forest Service, through their contractor Rogue Community College, and the DEQ which was conducting field work for development of the total maximum daily load (TMDL) analysis. A TMDL analysis was being conducted on the lake because of previous pH exceedences measured on the lake. In addition, the outlet of Diamond Lake was being sampled during the summer as part of a study of Lemolo Lake by PacifiCorp.

The purpose of this project was to assemble the data collected by the various organizations during 2001, develop a database for the data, review the quality of the data, provide interim interpretation of the data, and to offer suggestions to the Forest Service for future monitoring needs on the lake. The following report describes the database and results for the three remaining tasks listed above.

DEVELOPMENT OF THE DATABASE

The first step in developing the database involved selecting the type of software. Several database software packages specifically designed to deal with limnological data were evaluated in addition to more general database software packages. The database specifically developed for limnological applications had a number of built-in features that made them attractive for use with the Diamond Lake data. These features included preset data input routines, data flagging and quality control applications, and output routines commonly used for depth/time analyses. These attractive features were offset by relatively high initial software costs and the lack of transferability to other organizations within the Forest Service and among other agencies. For this reason, we elected (in concert with the Forest Service) to organize the data with Access® software already owned by the Forest Service and in widespread use.

Access is a relational database that can efficiently link related pieces of information through key fields. This allows the user to develop custom reports and analytical tools to explore relationships and better describe the data. In addition, filters can be added to parameters to guide the input process and notes can be added to supplement the data description. The primary thrust of the database development under this contract was to assemble and organize the data and use the database to assist in the analysis. However, because a number of the data files were obtained late in the schedule, it was necessary to conduct the data analysis in parallel with the database development.

Data sets were obtained in a variety of formats including hardcopy field sheets which needed to be entered into electronic spreadsheets, Excel flat files, Excel files imbedded with photographs and graphs obtained from websites, text files, and word-processing files. Virtually all files had unique structures and formats which required considerable manipulation before they could be entered into the Access database. In particular, most of the files were established in a page-process basis which was suitable for delivery of a single set of results to a client, but were not optimally arranged for timer-series analysis. This required a number of the data files to be transposed to arrange the parameters across the top of the data sheet.

A second aspect of the database development involved grouping similar files for inclusion into the same Access table. In most cases, the decision was made to separate like data based on the organization collecting the data because of issues related to how the data were collected in the filed or analyzed in the laboratory. For example, three organizations conducted *in-situ* profiles of water quality, but because of differences in instrumentation and operation of the instruments we felt it important to segregate the data into discrete units. A notable exception to this pattern is with the phytoplankton samples collected by several different organizations, but analyzed almost exclusively by one laboratory.

Another aspect of data handling involved determining where on the lake samples or *in-situ* data were collected. Most of the data sites were described in general terms (as in "north end of the lake") rather than with precise locations possible with current GPS

technology. For this reason, we developed a set of site codes to both standardize the naming conventions for sites and to assign geographic coordinates to the positions (Figure 2). In some cases, we estimated these positions based on maps developed in the field and converted these to coordinates based on superimposing the sites over a digital map of Diamond Lake. Thus, in many cases, the sites locations are only approximations of the actual sites.

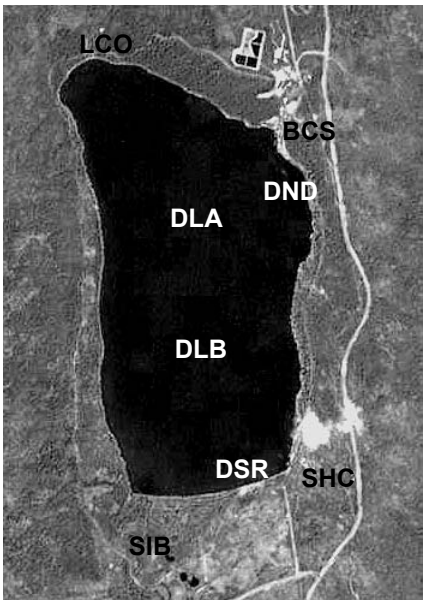

Figure 2. Location of primary sampling sites in 2001 and sites codes assigned for this project.

Questions regarding the disposition of some samples were difficult to resolve because the majority of the samples collected were not associated with chain-of-custody-forms or hard-copy field notes. Thus questions of location, date, and sample type were in some cases resolved on the basis of personal recollections. We believe that most of these issues have been resolved in this version of the database, but additional verification with the data originators would be advisable. We have provided suggested sample codes as a table in the database for both sites and sample types that could be used in the future to minimize issues of sample identification. A "Crosswalk" table has also been provided to indicate the data sources used in assembling the database and the dates associated with data collection.

The contract specified that data would be assembled for known data collected in calendar year 2001. The data collected on the lake spanned the period April 22 to September 27, however meteorological data were available for the entire year. In some cases such as the meteorological data from the UNF and NOAA, data for the entire period of record covering a number of years was included in the database. With the exception of impossible values (eg., pH > 14) and data subsequently identified by the originator as wrong (eg, dates in error or parameter headings switched), we have not intentionally altered the data from the original data sources. Issues of data quality are discussed in the following section.

DATA QUALITY REVIEW

The data assembled for the database were subject to review prior to interpreting patterns in the data. The types of data review varied depending on the nature of the data, documentation available for checking the data, and comparable data from other sources allowing for comparative analyses. The original intent of the data review was to be able to assign flags and qualifiers to the data to reflect the quality of the information. This was not possible for much of the data because of the lack of objective criteria that could be assigned to the data. For example, individual climatic data from UNF sites met acceptable standards for quality, but the value of the entire data record was questionable because forest canopy around the sites was allowed to encroach, thus altering annual patterns in wind velocity and other data. Consequently, we have elected to describe the quality of the data for data files, but not for individual datum. The data quality assessments were conducted from the perspective of limnologists attempting to use the data for interpretation and are considered relative to that objective.

A. Meteorological Data

There are no meteorological data collected at Diamond Lake with the exception of the automated snow pillow operated by the NRCS and climatic data collected at the sewage lagoons. Data relatively close to Diamond Lake were derived from the UNF, NOAA, and the NPS. The NPS collects data at two sites at Crater Lake, one on the rim and one on the lake. We selected the rim site to provide information more representative of conditions at Diamond Lake. The NPS site at Crater Lake has operated for the last decade, although only data from 2001 was uploaded to the database. Hourly data from the site were obtained on CD from OSU cooperators maintaining the site. No data quality issues were identified with these data. Longer-term precipitation data from post-1965 were derived from the Roseburg NOAA site by downloading information from their website. Although, minor portions of the data were missing, no data quality issues were evident. A supplemental NOAA precipitation site is operated at Lemolo Lake to the north of Diamond Lake. Again, no particular problems were noted in these data except for some missing values.

The UNF operates two weather stations in reasonable proximity to Diamond Lake at Tokatee Air Strip and Cinnamon Butte. These are RAWS stations operated for the purpose of assessing fire threat. An examination of the wind data from each of the sites shows that average wind speed has been declining (Figure 3). This is attributed to growth of the forest canopy around the perimeter of the site, thus altering the micro-climate at the respective sites (M. Jones, UNF, pers. comm., 2002). The data are useful for evaluating general climatic patterns within a year, but the data should probably not be used for assessing annual trends. The UNF also collects meteorological data at the sewage lagoons immediately north of the lake, but the data were not made available for entry into the database at this time.

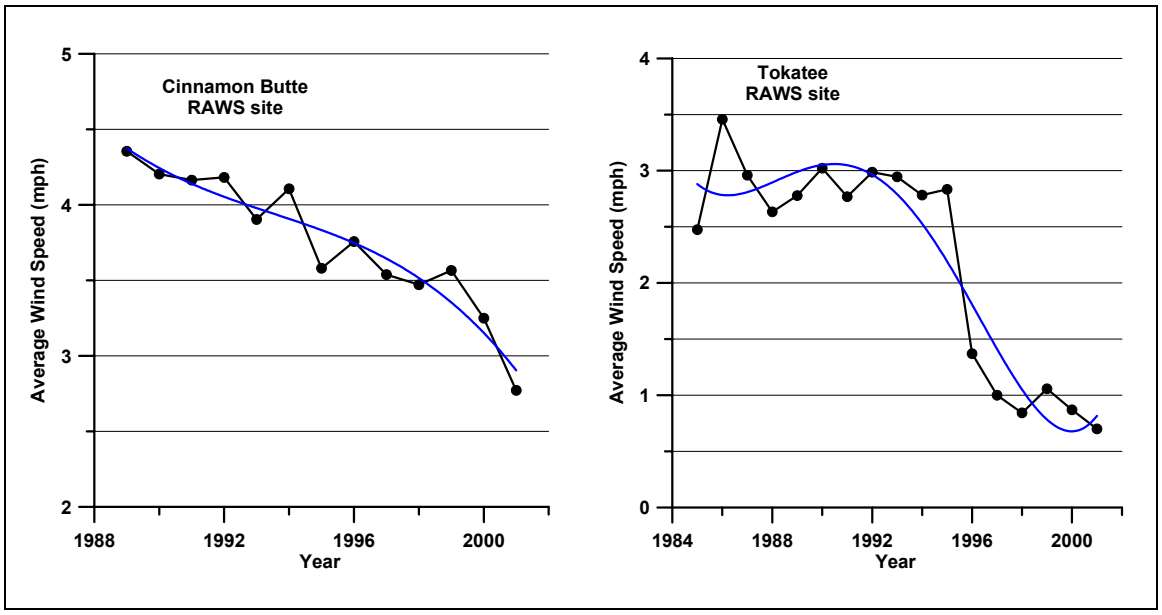

Figure 3. Annual average wind velocity measured at the two UNF RAWS weather stations.

B. Hydrological Data

The only continuous hydrological data collected at Diamond Lake is discharge at Lake Creek, the outlet from Diamond Lake. This site is operated by USGS and provisional data collected through September 2001 were made available to us in a text file. There were no data quality issues identified with this data set, although it should be noted that the flows are altered upstream of the gaging site by flash boards installed at the upstream weir. Lake stage (which is not currently measured) is maintained higher in the summer and the flash boards are removed in the fall allowing the stage to drop. The effect of the outlet control on flows measured in Lake Creek is evident in Figure 4.

The two permanent inflows to Diamond Lake, Silent Creek and Short Creek, are currently not monitored for flow on a routine basis. Silent Creek discharge was measured twice in May 2001 and Short Creek was measured once. Both sites have staff gages and discharge is believed to be relatively stable in these spring-fed streams. The repeated discharge measurements on Silent Creek were within 10% of one another. These data are listed in the supplemental hydrology table.

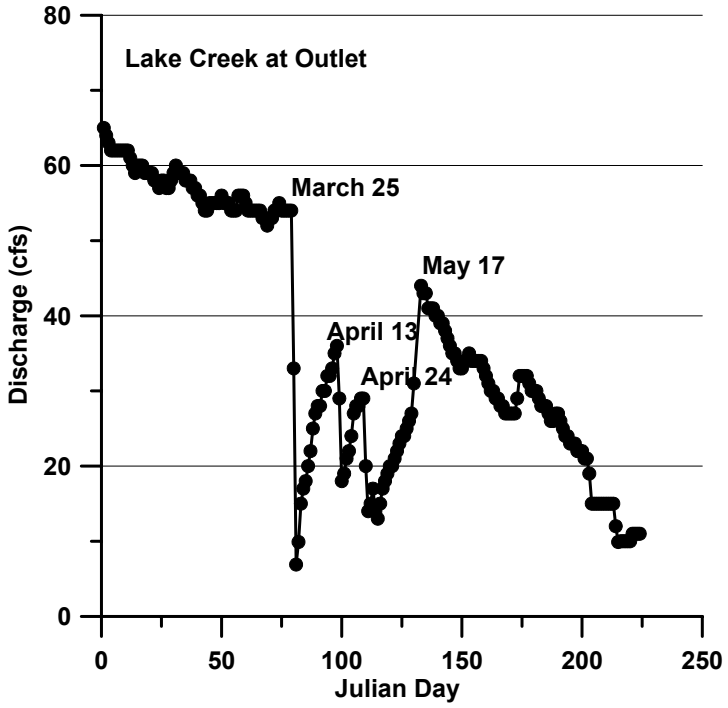

Figure 4. Discharge (cfs) measured at the outlet of Diamond Lake (Lake Creek) by USGS for 2001. USGS Station #14312500.

C. Oregon Department of Fish and Wildlife (ODFW) Data

ODFW staff were among the most active on Diamond Lake in 2001 with work on adjusting the flash boards at Lake Creek, conducting the Citizen Lake Watch Program, performing supplemental fisheries abundance studies, and providing additional dissolved oxygen/temperature data. The fisheries data included stocking records back to 1946 and angler harvest information on the trout. The Lake Watch file includes Secchi disk observations on 13 separate dates and the Fish Survey study includes four different dates at up to 27 different sites around the lake. These ODFW sites are cross-referenced with site codes established for the water quality work. Field header data were retained in a separate table. Fisheries biomass and trapping information collected in 2001 were still being compiled and are expected to be available in May 2002. No data quality issues were identified with these files, although it should be noted that the fish survey files were based on semi-quantitative data using an inexpensive hydroacoustic device.

D. Oregon Department of Environmental Quality (DEQ) Data

The DEQ had scheduled sampling of Diamond Lake in 2001 as part of the field effort to establish a total maximum daily load (TMDL) for the lake. Diamond Lake had previously been placed on the state 303(d) list for impaired water bodies because of pH exceedences (values > 8.5) in previous years. DEQ collected data in May, June, and August. All *in-situ* instrumentation was well-documented as were the collection of quality assurance samples and documentation of sample location and identification. No data quality issues were identified in either the field or the analytical data with the exception of some relatively high detection limits for some analytes and mislabeling of sampling site in the data file (this is corrected in the database). However, all parameters were clearly flagged for detection limit issues where appropriate.

E. Rogue Community College (RCC) Data

The RCC has been under contract with the UNF since 1992 to collect several samples per year on Diamond Lake and its major tributaries. Data collection has included collection of water samples for analysis of nutrients by the Forest Service Central Analytical Laboratory in Corvallis, collection of phytoplankton samples (described elsewhere), zooplankton (also described elsewhere), photometer data, light transmission data, and in-situ measurements. Diamond Lake was sampled five times by RCC in 2001. The data were for the most part extracted from the Cascade Research Group website. A review of the RCC data identified some areas of concern. First, the procedures used to collect the profile measurements (temperature, DO, pH, conductivity, turbidity, redox potential) do not conform to manufacturer's specification for stabile readings at depth. An examination of the field procedures shows that the multi-parameter probe was lowered on a continuous basis, thus never allowing some of the probes to stabilize. The effect on the measurements is that the values collected while lowering the probe are slightly different than when the measurements are recorded on the return to the surface (Figure 5). Since the probe is only held for sufficient periods while the instrument is at the surface and again at the bottom, values at other depths are likely to be in error. The magnitude of the error is probably relatively small, although the greatest error would be expected when the lake was stratified and the probe passed quickly through the thermocline.

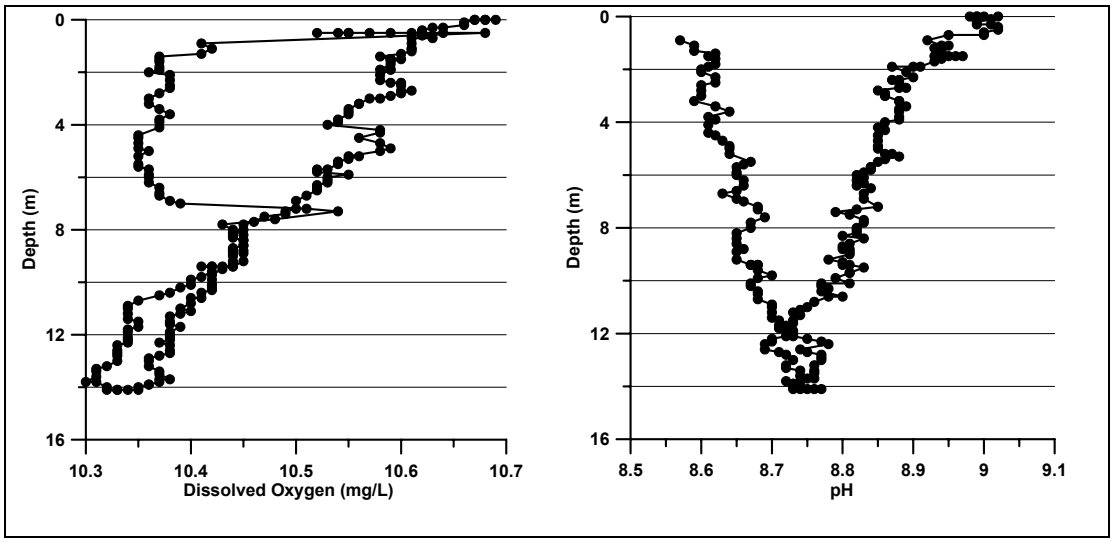

Figure 5. Dissolved oxygen and pH profiles measured in Diamond Lake in April 2001, by Rogue Community College. The different curves for each parameter represent the values measured while lowering and raising the water quality sonde.

A second issue with the profile data concerns the pH measurements. pH values measured by RCC are mostly greater than 8 (Figure 6), even those below the thermocline and the photosynthetic zone (based on Secchi disk transparency). The expected pH for Diamond Lake in equilibrium with atmospheric CO_2 (assuming alkalinity = 400 ueq/L and $P_{CO2} = 10^{-3.2}$ atm) is about 7.6. In hypolimnetic waters with dissolved oxygen depleted, the expected pH is considerably less than 7.6. In contrast, pH profiles for Diamond Lake measured by DEQ exhibit the expected CO_2 undersaturation in the epilimnion and super-saturation in the hypolimnion (presented later).

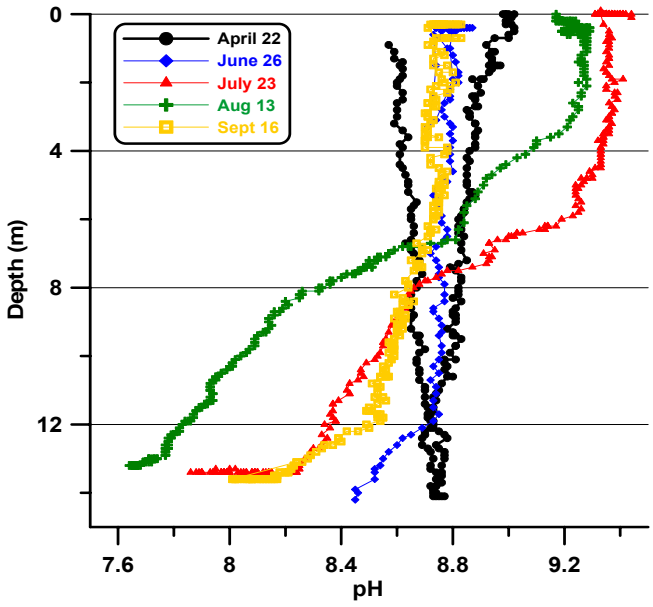

Figure 6. pH profiles in Diamond Lake measured by the RCC, 2001.

The third issue, although not technically an error, suggests that greater attention be given to parameter selection in the future. The values listed as total phosphorus in fact were run on the filtered aliquots, which means that these are not total phosphorus, but rather total dissolved phosphorus. On a related issue from the USFS laboratory, parameters that were labeled by the laboratory as "Total Nitrogen" were found to be "Total Kjeldahl Nitrogen" (because NO_3 had not been added to the TKN). These are now represented as TKN in the database.

Lastly, we were unable to locate any quality assurance blanks, duplicates, or reference samples collected by RCC. However, the USFS analytical laboratory performs a number of internal duplicates. In addition, a number of external check samples submitted by PacifiCorp during summer 2001 for the Lemolo Lake project indicated that the laboratory performance was very good (Eilers and Raymond, unpublished data).

F. JC Headwaters, Inc. (JCH)

A small portion of data collected in August from Diamond Lake and the outlet was added to the data base. This consisted of profiles of temperature, conductivity, and dissolved oxygen. pH was excluded from the data file prior to submission because even though the probe compared well with buffered solutions, the *in-situ* measurements were judged to be in error (all values below pH 7). The probe was subsequently replaced. Other values appeared to be within expected ranges. JCH also collected supplemental hydrological data at the Lake Creek outlet for PacifiCorp, which agreed reasonably well with DEQ for Silent Creek and several phytoplankton samples.

G. Aquatic Analysts (AA)

Aquatic Analysts provided nearly all results for phytoplankton community composition from Diamond Lake in 2001. The Excel files were transposed and concatenated into a comprehensive phytoplankton table. PacifiCorp collected several quality assurance splits for phytoplankton on September 5, 2001 from Lake Creek and sites on the Lemolo Lake system. The results showed good agreement between Aquatic Analysts and Phycotech for three of the four splits (Table 2). The third laboratory, BSA Environmental Associates, showed little agreement with the other two laboratories. An on-site microscopic examination of phytoplankton in Diamond Lake in August by J. Kann also showed that *Anabaena* was the dominant cyanobacteria which agreed with results from AA and Phycotech. Although we have high confidence in the taxonomic characterization of the phytoplankton, there remain some issues regarding how to quantify the biovolume of these filamentous taxa. Efforts are underway to standardize the phytoplankton quantification in Diamond Lake for subsequent years.

Table 2. Phytoplankton samples results split among three laboratories for sites on the Lemolo Lake Study, September 5, 2001 (data courtesy of PacifiCorp).

Algae Split Sample Comparison — Lemolo Lake Study Sept 5/6, 2001

Dominant Taxa (Relative % biovolume)

Site	Aquatic Analysts		PhycoTech		BSA	
	Taxa	%	Taxa	%	Taxa	%
BSODA	*Anabaena planctonica*	34	*Cymbella affinis*	19	*Fragilaria capucina*	23
	Cocconeis placentula	9.3	*Anabaena planktonica*	18	*Cocconeis placentula*	16
	Fragiliaria vaucheria	7.5	*Cocconeis placentula*	13	*Oscillatoria minima*	15
	Achnanthes lancelota	7.3	*small flagellate*	9.2	*Fragilaria construens*	8
	Cymbella affinis	6.1	*Cocconeis sp.*	4.3	*Oscillatoria limnetica*	6.2
LEMLKT	*Anabaena planctonica*	90	*Anabaena planctonica*	98	*Asterionella formosa*	54
	Fragilaria crotonensis	5.8	*Scenedesmus longus v.*	2.7	*Anabaena macrospora*	33
			Melosira granulata	2	*Chlamydomonas*	4.9
LEMLLT	*Anabaena planctonica*	98	*Anabaena planctonica*	92	*Anabaena macrospora*	42
	Asterionella formosa	1.2	*Cosmarium*	1.3	*Asterionella formosa*	27
					Aulocoseria granulata	14
					Chlamydomonas	8
					Pandorina morum	3.5
LAKEFS	*Fragilaria crotonensis*	40	*Microcystis aeruginosa*	15	*Aulocoseria granulata*	45
	Cryptomonas erosa	29	*Cryptomonas erosa*	12	*Rhodomonas minuta*	18
	Synedra radius	9.4	*Staurastrum dijectum*	12	*Fragilaria crotonensis*	17
	Glenodinium sp.	4.6	*Uroglena*	8.7	*Rhodomonas minuta v.*	5.6
	Melosira ambigua	4.6	*Cymbella navicula*	8.7	*Elakatothrix gelatinosa*	2.2

Where BSODA = below Soda Springs Dam; LEMLKT = Lemolo Lake, near dam, epilimnion; LEMLLT = Lemolo Lake, mid-lake, epilimnion; and LAKEFS = Lake Creek at outlet of Diamond Lake

H. ZP Taxonomic (ZPT)

ZPT conducted the taxonomy of the zooplankton samples collected by RCC. The text files were converted into Excel files, transposed, and concatenated. We are unaware of any split samples for the zooplankton to judge the quality of the taxonomy, although the samples were preserved and presumably could be made available to other taxonomists for analysis.

I. Wright State University (WSU)

The anatoxin and microcystin analyses of the lake samples were conducted by Dr. Wayne Carmichael. Most of these samples were collected by UNF staff and sent directly to WSU. We were unable to locate any chain of custody forms or field notes to resolve uncertainties regarding where on the lake the samples were collected. We relied for the most part on the labels on the samples as recorded by WSU. The data were extracted from a Word file report and entered into separate tables for each toxin. The toxin analyses included analysis of duplicates and reference samples, indicating that there were no apparent issues regarding the quality of the analytical results.

J. Photographs

Photographs of Diamond Lake were collected from the UNF, RCC, and JCH. The UNF aerial photographs taken by staff in the fire patrol aircraft were digitally scanned and entered as jpegs. The images on the RCC website were extracted and placed in an Excel file. The JCH images already existed as jpegs. To avoid unnecessarily increasing the size of the database, the photographs were placed on a separate CD and referenced with an index file in the Access database.

DATA ANALYSIS

The data analysis focused on two areas: (1) water quality and (2) patterns in phytoplankton community composition and toxins. This is not meant to be an exhaustive analysis of the data (which would require examination of data from previous years), but was conducted with the primary objective of offering insight into possible causal factors associated with the cyanobacterial bloom in summer 2001 and identifying opportunities to improve lake monitoring in subsequent years.

A. Water Quality- *In Situ* Measurements

(1) Temperature

The water temperature is an important factor in limnological analyses because it affects the rate of biochemical reactions and, combined with wind and lake geometry, determines the degree that the lake stratifies. Diamond Lake is sufficiently deep (max depth 15m) to stratify, but because of its elevation (1580 m) it is prone to de-stabilization during cool periods. The temperature profiles indicate that the lake was well mixed throughout the upper 12 m in June and only developed more prominent stratification in July and August (Figure 7). In September, the lake became homothermic again. The lake reached a maximum surface temperature near 21°C in early August. The weather patterns in 2001 showed the presence of two distinct warm periods peaking in early July and early August. These are discussed later in the report in the context of the phytoplankton variations.

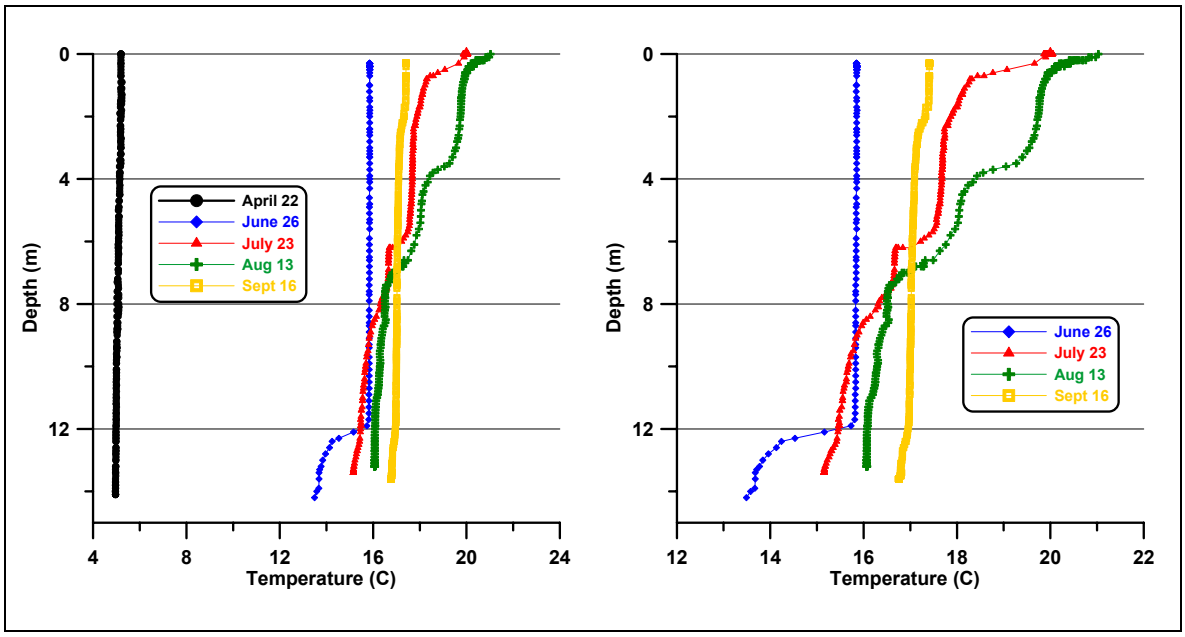

Figure 7. Temperature profiles measured in Diamond Lake in 2001 by Rogue Community College. The figure on the right is the same data with the month of April excluded to allow for an expanded scale in the warmer months.

(2) Specific Conductance

Diamond Lake became slightly more elevated in total ions (as represented by specific conductance) from spring to summer, presumably as the snowmelt was gradually supplanted by a higher percentage of groundwater input (Figure 8). In addition, ions and metals released from the anoxic sediments in the summer could contribute to increasing the summer conductivity in the lake.

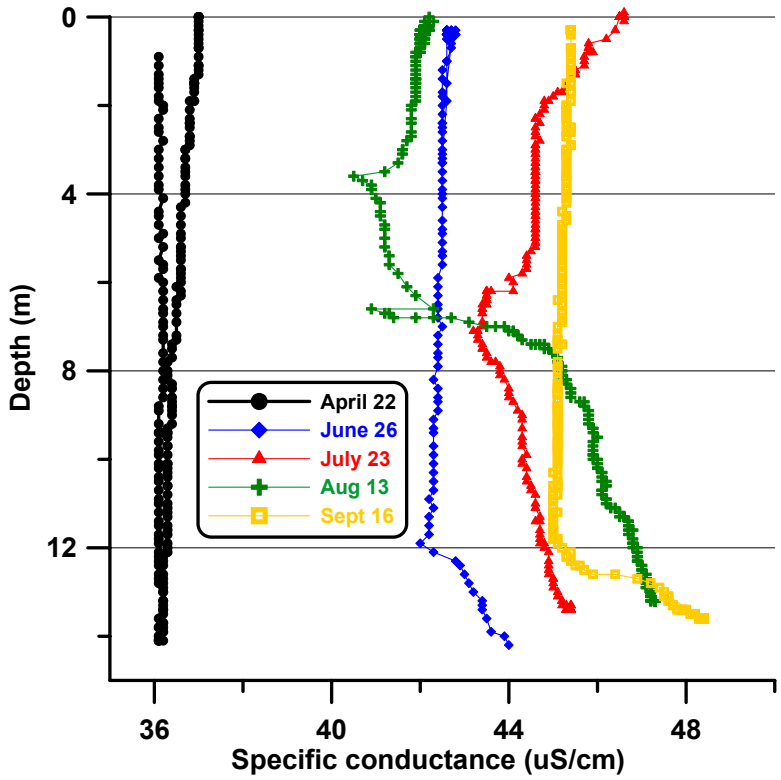

Figure 8. Specific conductance profiles in Diamond Lake collected by RCC in 2001.

(3) Turbidity

Turbidity increased an order of magnitude from the spring to the summer (Figure 9). We attribute nearly all of this increase to algal turbidity as illustrated by the higher values in the epilimnion in July. Turbidity data were not available for August.

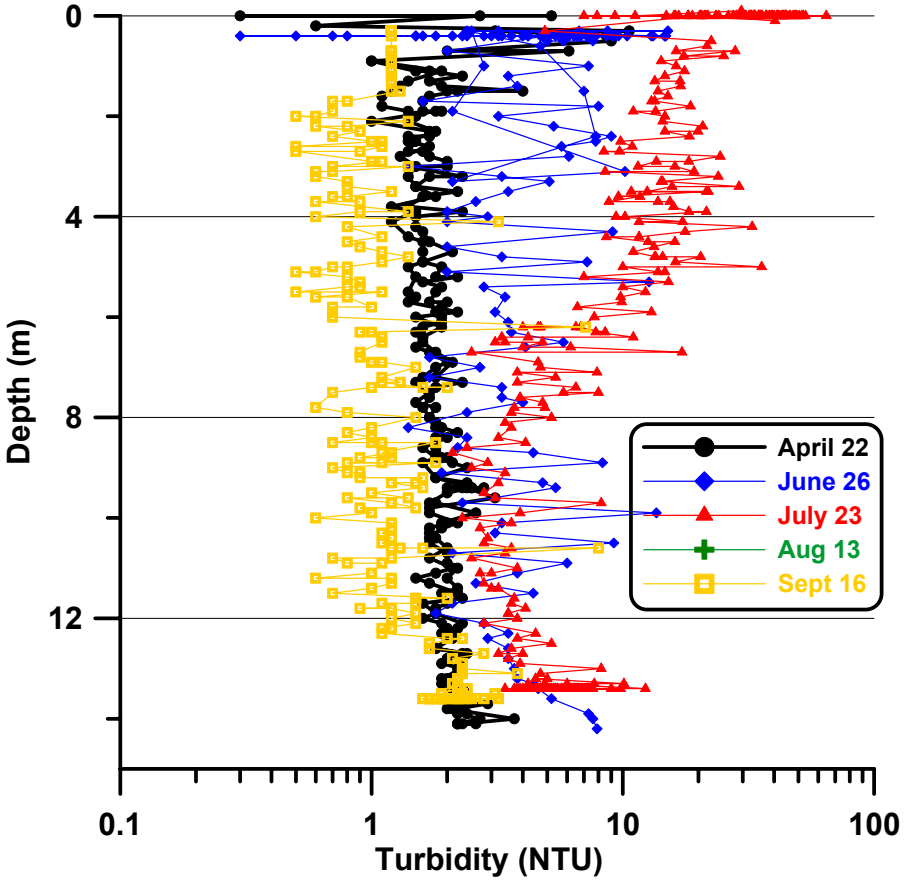

Figure 9. Profiles in turbidity in Diamond Lake measured by RCC in 2001.

(4) Redox Potential

Redox potential (pE) is a measure of free energy change per mole of electrons for a given reduction reaction. Like pH, pE is an intensity factor. In strongly oxidizing solutions, the pE will be high (eg ~ 500 mV) and in strongly reducing environments the pE will be low (eg ~ 200 mV). Because pE is related to the 4^{th} root of dissolved oxygen concentrations, it is insensitive to change until nearly all DO is depleted. The pE for most of the sampling dates was uniform from top to bottom, but in August when DO was absent below 8m the pE showed a rapid decrease with depth (Figure 10). Because pE is strongly influenced by iron reactions, the decrease in pE was probably accompanied by a major increase in hypolimnetic iron (as Fe^{2+}) and phosphorous.

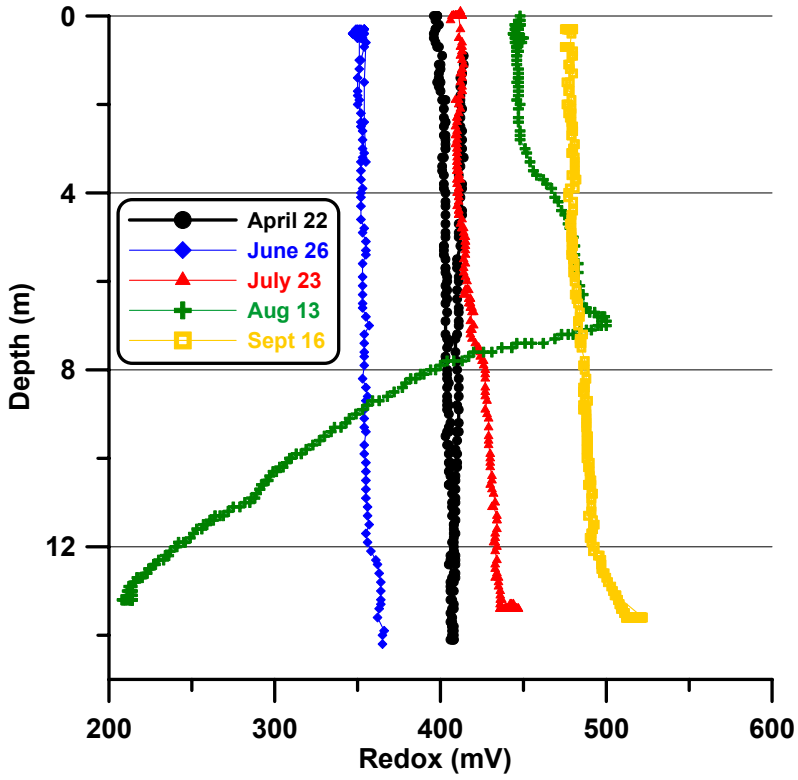

Figure 10. Redox potential measured in Diamond Lake by RCC in 2001.

(5) pH

As noted in the data review section, there is concern that the RCC pH data for 2001 is not accurate and the JCH pH data was previously discarded. We have relied on the DEQ pH values from May, June, and August as the best measures of pH conditions in Diamond Lake in 2001 (Figure 11). The data indicate that epilimnetic pH values are indicative of undersaturation of CO_2 caused by high rates of primary production. This is particularly evident in August when pH values exceeded 9.0. DEQ recorded a maximum pH value of 9.18 in the morning at the southern end of the lake in August. pH values in the hypolimnion indicated that CO_2 was slightly supersaturated, likely as a result of decomposition reactions.

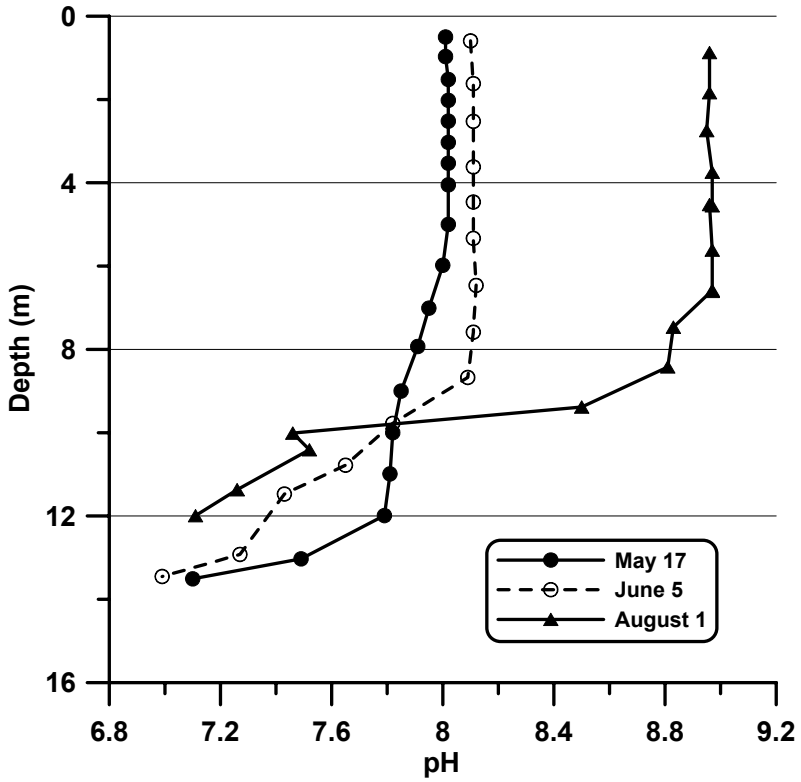

Figure 11. pH profiles measured in Diamond Lake by DEQ in 2001.

(6) Dissolved Oxygen

Dissolved oxygen (DO) concentrations were at or near saturation in the epilimnion for all sampling periods except August when DO was below saturation even at the surface (Figure 12). Comparison with DO measured by both DEQ and JCH also indicate DO undersaturation in August (Figure 12). The DO concentration expected for waters at this elevation and temperature are about 7.5 mg/L (based on USGS tables). The data indicate a progressive and widespread depletion of oxygen in Diamond Lake as the cyanobacteria population died back. This may also explain the unusual color of the lake in August as cyanobacterial pigments were released during cell lysis.

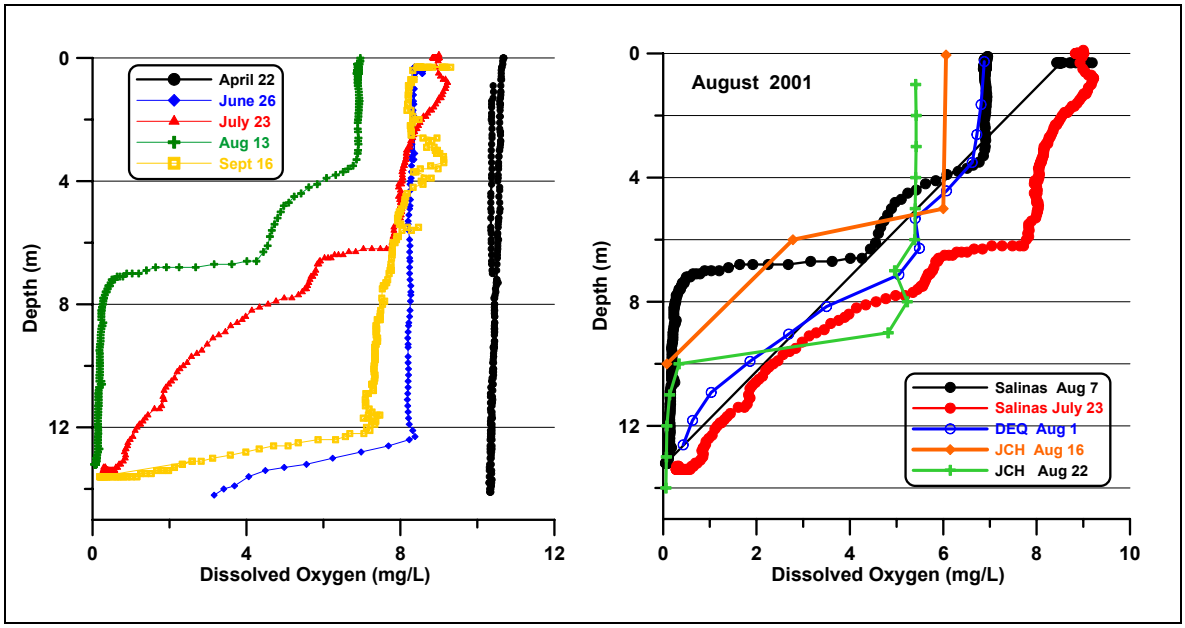

Figure 12. Dissolved oxygen profiles in Diamond Lake collected by RCC (left) and DO profiles collected by RCC, DEQ, and JCH in August, 2001 (right).

(7) Secchi Disk Transparency

Secchi disk transparency exhibited a sharp decline in the summer, reaching a minimum at the end of July (Figure 13). The relationship of transparency to lake temperature and phytoplankton abundance is discussed later in the section dealing with the phytoplankton.

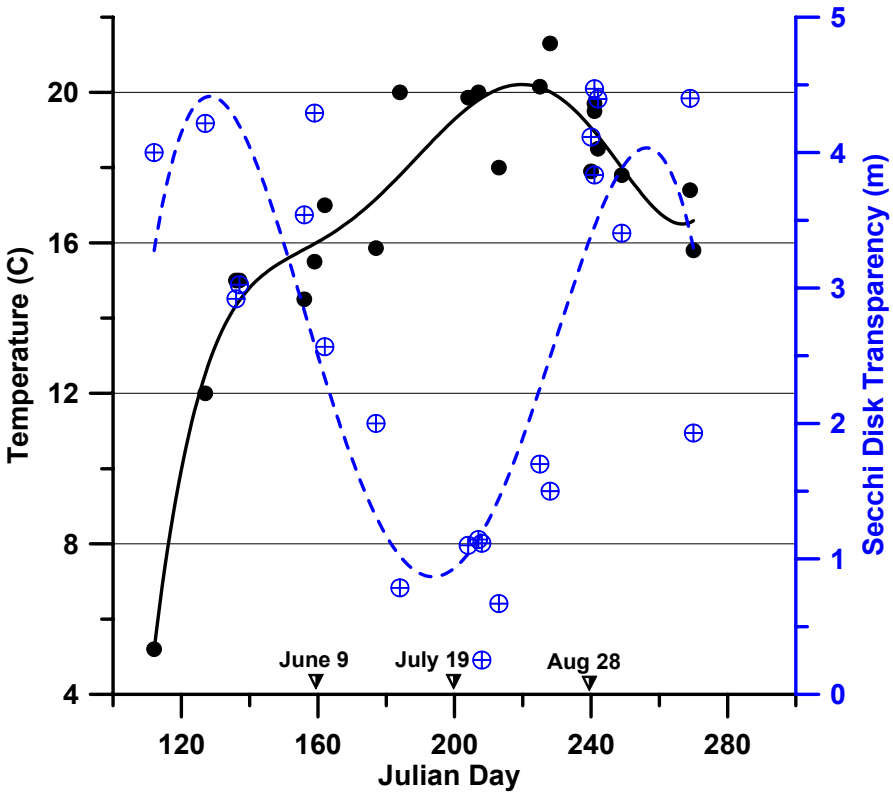

Figure 13. Secchi disk transparency (in blue) plotted against lake surface temperature (left) in Diamond Lake, 2001.

B. Water Quality -- Analytical Data

(1) Phosphorus (based on USFS data)

Total dissolved phosphorus exceeded PO_4 values in all cases (Figure 14), which is expected. Phosphorus values remained relatively unchanged within sites over the summer. Concentrations of PO_4 were typically about 55 *u*g/L for both of the major tributaries and were about 1 to 2 *u*g/L in the lake (Figure 15). Concentrations in the lake were relatively unchanged with depth, which is somewhat surprising for the deepest samples during anoxic conditions. The almost complete uptake of available phosphorus in Diamond Lake indicates that phosphorus is the limiting or co-limiting (with N) nutrient.

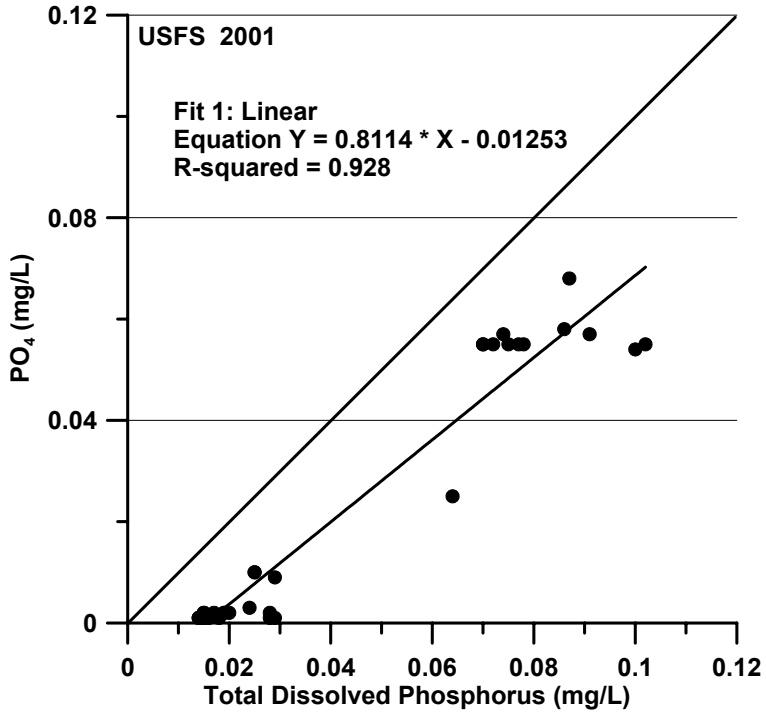

Figure 14. Total dissolved phosphorus versus ortho-phosphorus for samples collected by RCC and analyzed by the USFS laboratory. The 1:1 and the least-squares best fit are presented for the data.

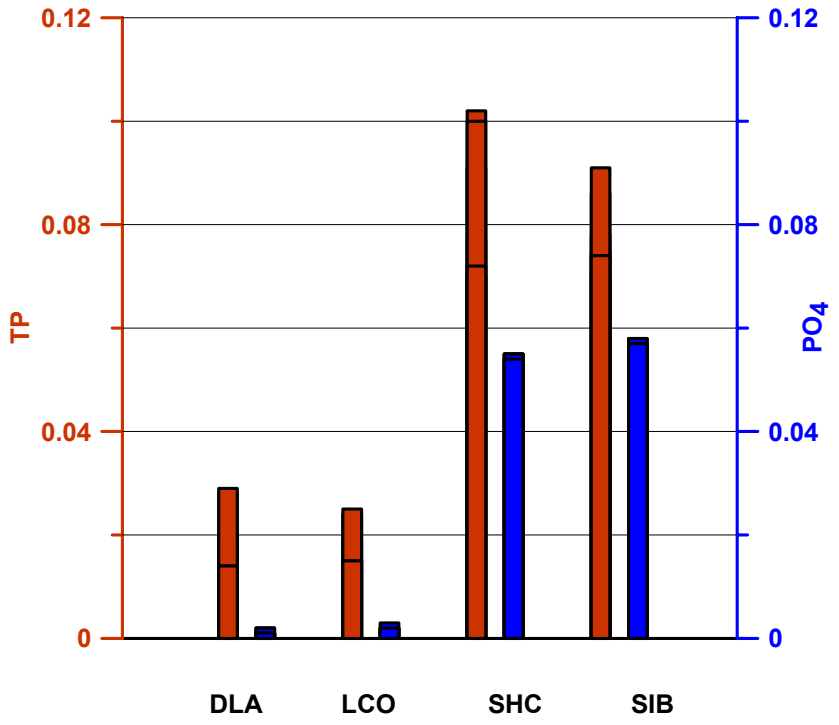

Figure 15. Total dissolved phosphorus and ortho-phosphorus (mg/L) collected by RCC and analyzed by the USFS laboratory for the deep lake station (DLA), the lake outlet (LCO) and the two principle inlets, Short Creek (SHC) and Silent Creek (SIB).

(2) Nitrogen

Three forms of nitrogen were measured, total Kjeldahl nitrogen [TKN] (on filtered and unfiltered samples), nitrate [NO_3 – N], and ammonia [NH_3 – N]. The comparison of TKN with DKN shows that the unfiltered component of organic nitrogen was nearly twice that of the dissolved component – again, an expected finding, which reflects the phytoplankton present in the water (Figure 16). Almost no measurable NO_3 or NH_3 is present in the Silent Creek inflow, although there is appreciable NO_3 present in Short Creek (Figure 17). Both NO_3 and NH_3 are present in relatively high concentration in Two Bear Creek adjacent to the Diamond Lake Resort. Both NO_3 and NH_3 are largely below detection limits in the surface waters of Diamond Lake. However, the hypolimnetic waters of Diamond Lake developed high concentrations of NH_3 as the dissolved oxygen became depleted in the hypolimnion during the summer (Figure 18). An examination of the three principle components of aqueous nitrogen shows that the waters entering the lake are predominantly inorganic nitrogen (as NO_3), where as the lakewater nitrogen is nearly all in reduced form, largely as organic nitrogen.

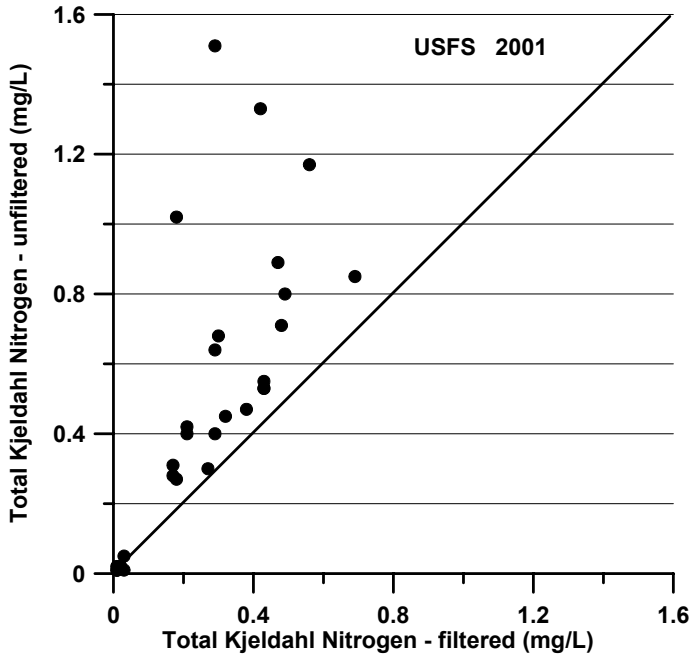

Figure 16. Total Kjeldahl nitrogen in filtered and unfiltered samples.

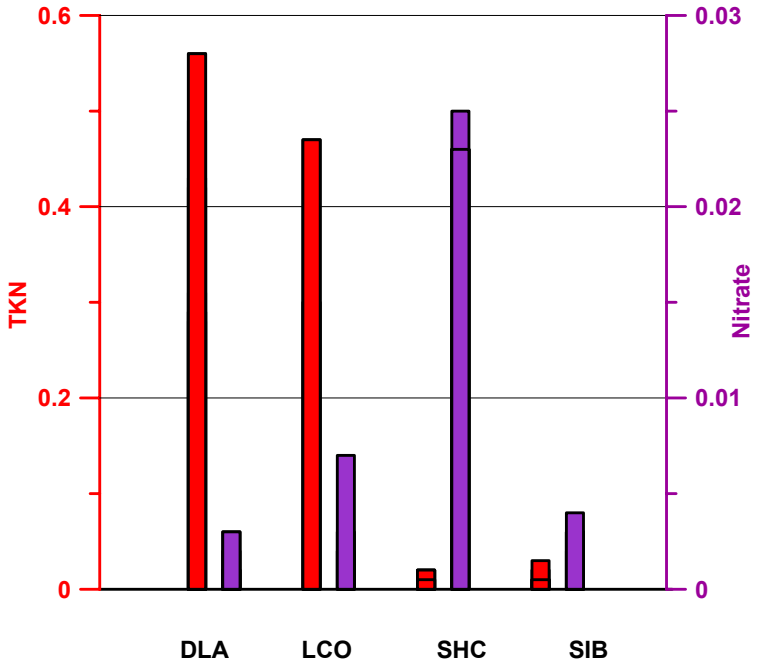

Figure 17. Total Kjeldahl nitrogen (red) and nitrate (purple) for lake and stream sites (in mg/L – N).

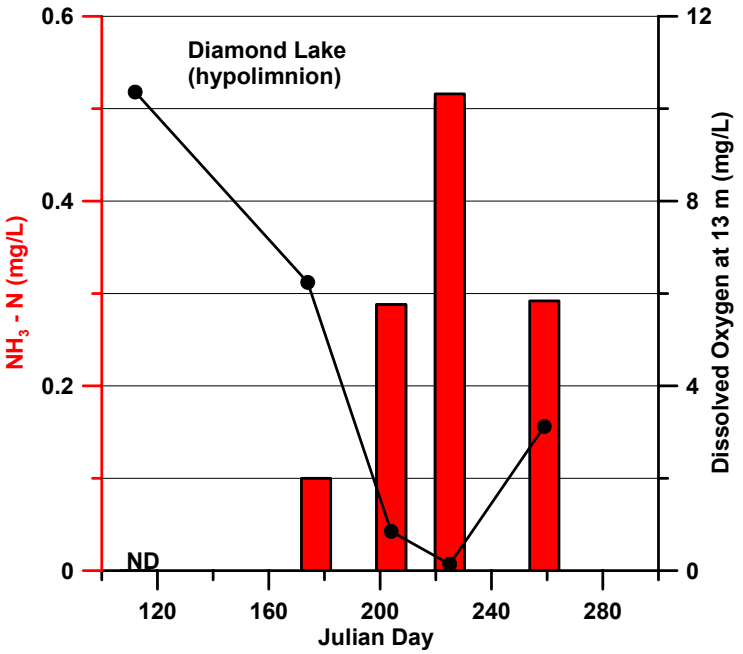

Figure 18. Ammonia measured in the hypolimnion of Diamond Lake in 2001 (red bars) compared with hypolimnetic concentrations of dissolved oxygen.

The nitrogen and phosphorus data illustrate that Diamond Lake is retaining large amounts of phosphorus and exporting even greater amounts of organic nitrogen (Figures 15 and 17). Assuming an inflow rate of 30 cfs, we estimate that the lake is retaining about 0.8 metric tons of phosphorus from April through September and is exporting about 11 metric tons of organic nitrogen during the same period (assuming a discharge of 1 m^3/s X 15.552 x 10^6 sec X 5x 10^{-2} g/m^3 of P and 7 x 10^{-1} g/m^3 of N). These estimates ignore contributions from other sources such as atmospheric inputs, waterfowl, and fish stocking.

(3) Silica

Concentrations of silica in Diamond Lake are more than ample to support abundant populations of diatoms. However, the data indicate that a considerable amount of silica is lost to the lake sediments through deposition of diatom frustules as indicated by the difference in concentrations of silica between the inlets and the lake (Figure 19). Using the same assumptions described above for flow, we estimate that the sediment accumulates 170 metric tons of silica from April through September. The plot of silica versus conductivity confirms that the difference in concentration of silica from the inlets to the lake is caused by a loss of silica rather than a substantial dilution of ions (Figure 20).

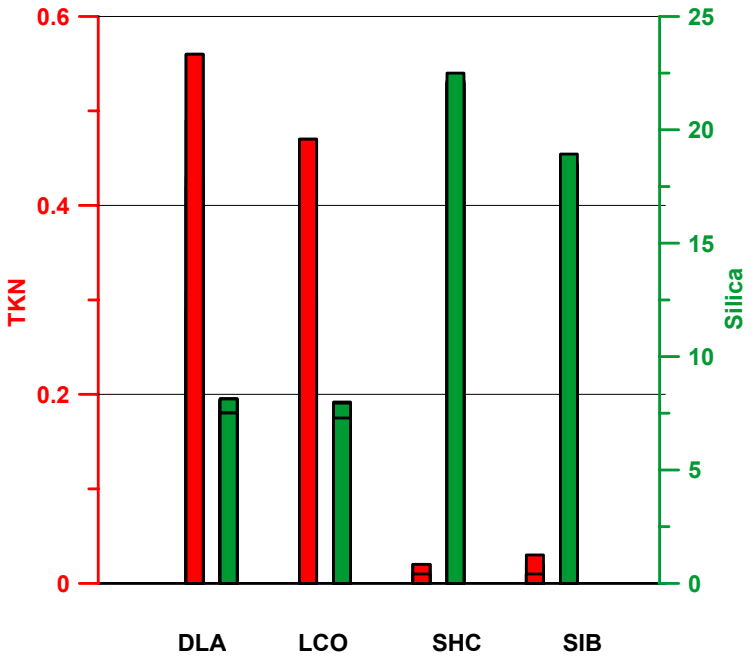

Figure 19. Lake (DLA and LCO) and stream (SHC and SIB) concentrations of silica (green) compared to total Kjeldahl nitrogen (all in mg/L).

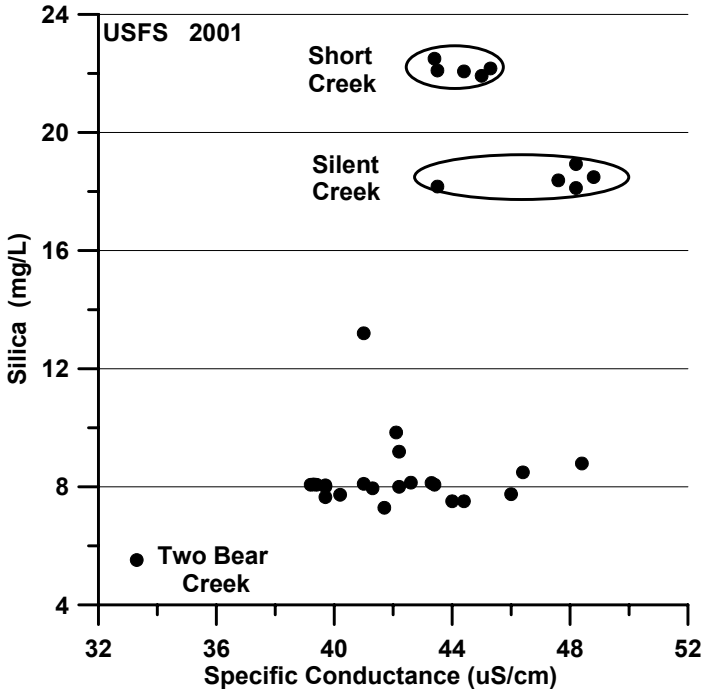

Figure 20. Comparison of silica concentrations versus specific conductance for the principle inlets (circled values) versus the lake values, which generally have a silica concentrations near 8 mg/L.

(4) Alkalinity

Alkalinity values are relatively similar among lake and stream sites. The mean concentration for the total 35 samples from all sites analyzed by the UFSF lab in 2001 was 5.26 mg/L (as HCO_3-C) with a standard deviation of 0.42 mg/L. The slightly lower alkalinity values in the lake could be related to dilution from precipitation on the lake surface or from loss of carbonate to the sediment. The expected relationship between alkalinity and pH indicates that pH values in the surface waters of the lake are substantially above equilibrium values based on reasonable assumptions for atmospheric CO_2 (Figure21).

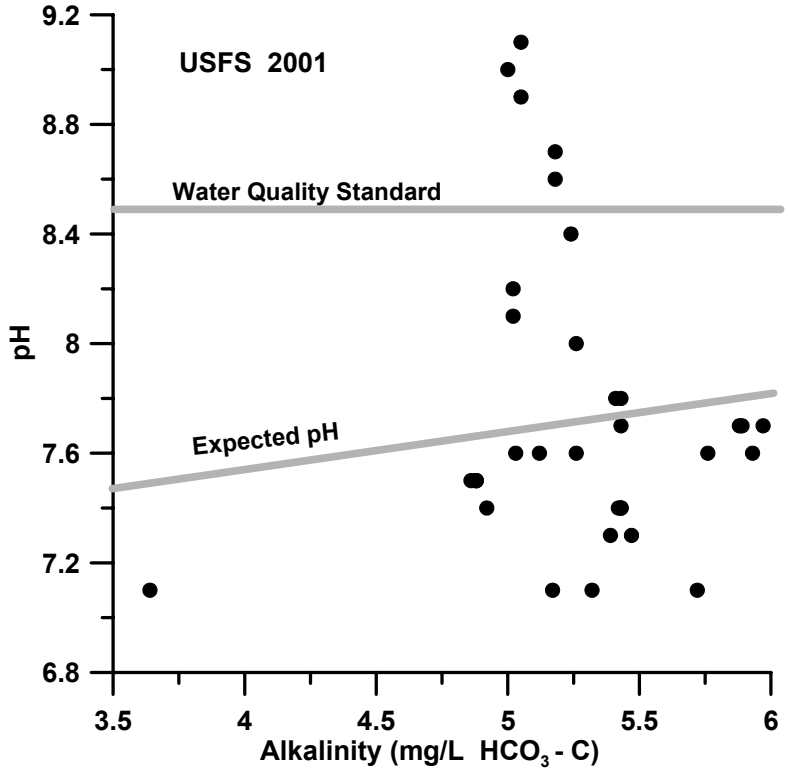

Figure 21. pH versus alkalinity for samples from Diamond Lake analyzed by the USFS laboratory. The values above pH 8 are all epilimnetic waters. The expected relationship was calculated assuming a P_{CO2} value of $10^{-3.2}$ atm.

(5) Chlorophyll *a*

Chlorophyll *a* reached a maximum concentration of 63.4 *u*g/L in the center of Diamond Lake (Figure 22), a value which was probably exceeded along the lake perimeter and the southern area of the lake during the peak bloom conditions (based on a Secchi disk value of 0.25 m recorded at the southern end of the lake). Chlorophyll values this high are clearly indicative of a hypereutrophic condition.

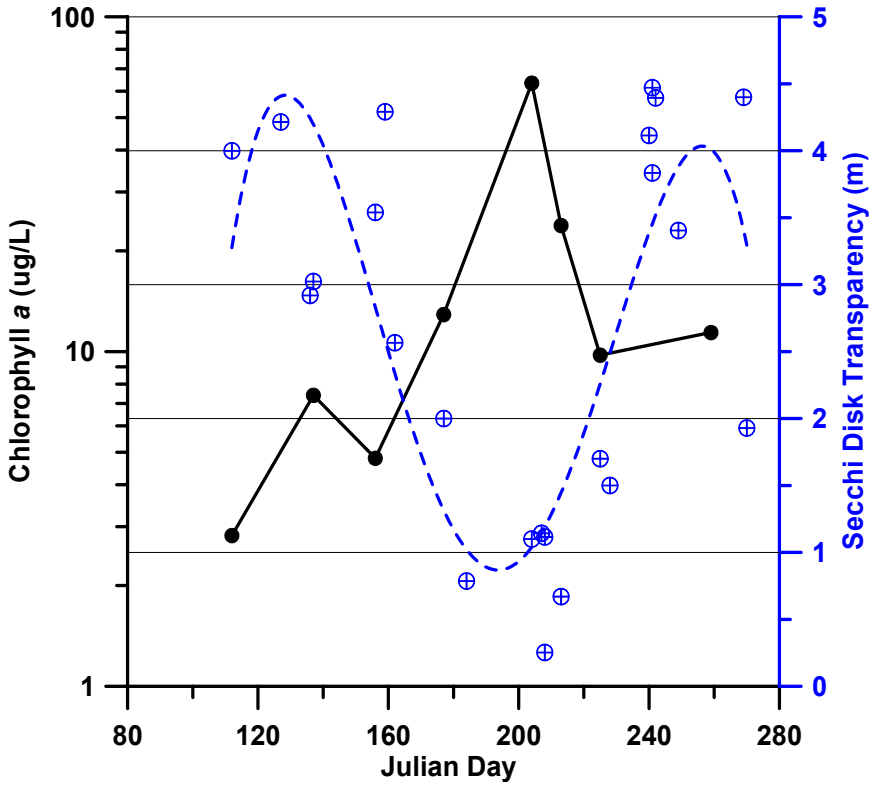

Figure 22. Relationship between chlorophyll *a* and Secchi disk transparency for Diamond Lake, 2001.

(6) Major Ions

Diamond Lake and its tributaries are Ca:Na:Mg/HCO_3 waters with little deviation in major ions among the different sites (Figure 23). The high silica concentrations shown in Figure 18 are indicative of silicate weathering of the volcanic andesites and rhyolites in the area. Precipitation during 2001 was well-below normal (Figure 24) which could have caused a slight increase in the ionic strength of Diamond Lake above typical values.

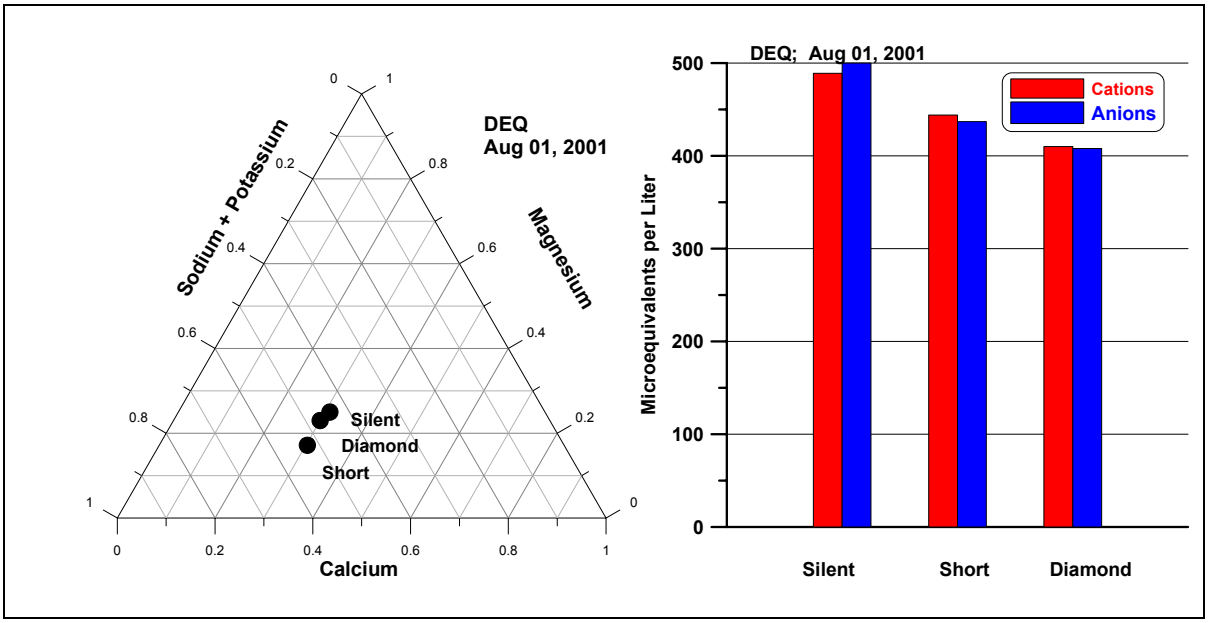

Figure 23. Proportion of major cations among the two major inlets and Diamond Lake (left) and concentrations of the sum of major cations and anions for the same three sites (right). All data from DEQ, 2001.

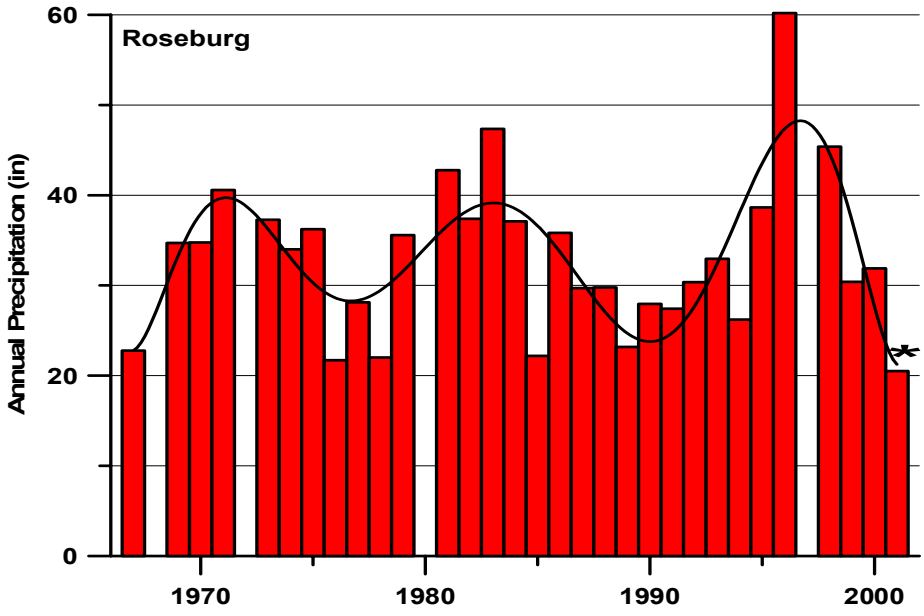

Figure 24. Annual precipitation in Roseburg, OR since 1966, shown with a polynomial fit of the data. The data for 2001 was slightly incomplete.

C. Phytoplankton

(1) Background

A major bloom of toxic algae occurred in Diamond Lake during the summer of 2001. Incidental observation during routine monitoring on July 25th of nearby systems indicated that a large algal bloom was occurring in Diamond Lake. Subsequent algal identification and quantification revealed that the bloom consisted of *Anabaena flos-aquae* (*Afa*), some strains of which are known to produce potent neurotoxins. Further laboratory analysis confirmed that this was indeed a toxic *Afa* strain, with significant measured concentrations of the neurotoxin anatoxin-a. The Umpqua National Forest (UNF) in conjunction with the Oregon Health Division issued a series of Water Quality Alerts, ultimately closing the lake to boating and contact recreation as *Afa* cell counts increased sharply during the first week of August. Routine bimonthly to monthly monitoring data were collected by Rogue Community College (RCC) as part of an ongoing annual sampling program at Diamond Lake. Additional samples for phytoplankton and algal toxin analysis were collected specifically in response to the toxic bloom. The purpose of this section is to provide a review of events and data relevant to the 2001 toxic algal bloom.

(2) Review of Data Sources

Phytoplankton and toxin samples were collected at five locations (Figure 2) over the course of the summer. Samples were collected on four sample dates by RCC at the DLA station using a Van Dorn style sampler at the surface, Secchi depth and 3x the Secchi depth. Surface grab samples were collected starting in late July at LCO (JC Headwaters for PacifiCorp), and DND and DSN (UNF and JC Headwaters). Two samples were also collected at sites DLA and DLB on August 17th by concentrating with a Wisconsin Plankton Net with 64-µm mesh. In addition, an on-site survey consisting of microscopic examination of samples from 5 shoreline sites was performed on August 28th (Kann 2001).

Unpreserved samples were shipped overnight mail to the laboratory of Dr. Wayne W. Carmichael at Wright State University in Dayton, Ohio. These samples were analyzed for two algal toxins that can be associated with *Afa*; microcystin-using enzyme linked immunosorbent assays (ELISA), and anatoxin-a using liquid chromatography/mass spectroscopy (LC/MS) methodology.

Additional samples preserved with Lugol's Iodine were sent to the laboratory of Jim Sweet at Aquatic Analysts in Portland, Oregon. These samples were microscopically analyzed for density and biovolume of phytoplankton species.

(3) Results and Discussion

(i) *Phytoplankton Biovolume*

An examination of phytoplankton biovolume collected from the surface of routine monitoring station DLA indicates that on the April 22nd and June 26th sample dates algal biomass was low relative to the mid-summer algal bloom (Figure 25a), and was dominated by species other than toxigenic *Afa* (Figure 25b). Despite the two-month gap between these two sample dates it is likely, based on Secchi disk, water temperature, and chlorophyll (Figures 13 and 22), that a major bloom did not occur prior to June 26th. Overall biovolume then increased substantially by the July 23rd sampling date, with *Afa* biovolume reaching ~8 mm^3 L^{-1} and comprising 80% of the biomass (Figure 25 a,b).

During the week following the July 25th determination at the Lake Creek Outlet site (LCO) that the bloom consisted of potentially toxic *Afa*, regular sampling was initiated by UNF at a dock just south of the Diamond Lake Lodge (DND) and at the dock near the

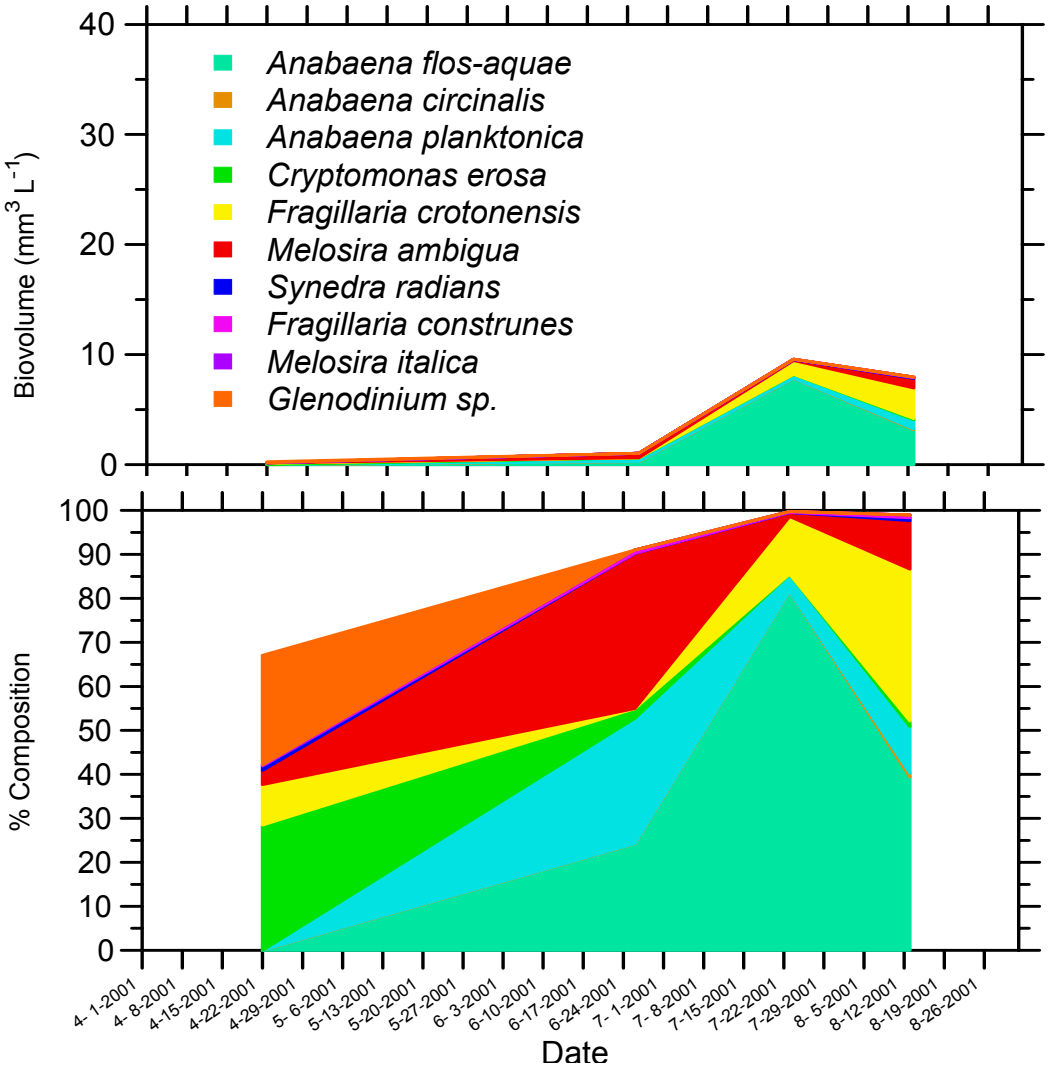

Figure 25. Phytoplankton biomass (a, top) and percent composition (b, bottom) at North Boat sample station (DLA - surface), Diamond Lake, 2001. Samples were collected by RCC as part of routine monitoring program.

most southerly boat ramp (DSR). At both locations these data indicate that on the August 1st sample date *Afa* comprised only ~55 % of the phytoplankton biomass, and maximum *Afa* biomass was less than 3 $mm^3 L^{-1}$ (Figure 26).

Thus, a decline in *Afa* appears to have occurred in the 9 days following the July 23rd sample date at DLA (Figure 25). Moreover, *Fragilaria crotonensis*, a large colonial diatom, accounted for 20% of the phytoplankton biovolume at DND on August 1st (Figure 26b). Diatoms as a group represented 30% of the biovolume on this date (Figure 26a). However, by the following week (Aug 6th), *Afa* rebounded, peaking at ~10 $mm^3 L^{-1}$ at DND and at ~37 $mm^3 L^{-1}$ at DSR, and accounted for 80-95% of the total biovolume (Figure 26b,d). Biomass levels then declined (first slowly and then rapidly) during the following 10 days, and by August 16th *Afa* was less than 1 $mm^3 L^{-1}$ and comprised less than 25% of the total biovolume. Percent composition of both diatoms (particularly *Fragilaria crotonensis* and *Melosira ambigua*) and Cryptophytes (*Cryptomonas erosa*) increased substantially through the rest of August and into September.

(ii) *Afa Cell Density and Human Health Guidance Levels*

In general, most literature dealing with toxic cyanobacterial blooms uses the measure of cells per ml when discussing critical bloom levels relative to human health (Chorus and Bartram 1999). Because algal density as reported by Aquatic Analysts was provided in algal units per ml (units being colonies of *Afa* in this case) and not cells per ml, *Afa* biovolume was converted to cells per ml by dividing total *Afa* biovolume by the biovolume for an individual *Afa* cell (given as 65 cubic micrometers: personal communication Jim Sweet).

Converted data were plotted for all sample locations and data points were fitted with a general trend line to determine seasonal trends in *Afa* density (cells ml^{-1}) and to evaluate density relative to guidance levels (Figure 27c). Human health guidance levels were derived from Yoo et al. (1995) and Chorus and Bartram (1999). The first level is termed Alert Level 1 (or sometimes vigilance level) and occurs when cyanobacterial cell density exceeds 500 cells ml^{-1}. At this point, if the species is known to be toxigenic, sampling is increased both temporally and spatially. The next level is Alert Level 2 and occurs when cell density exceeds 2000 cells ml^{-1}. At this point warnings are posted and lake users contacted to alert them of the presence of toxic algae and provided instructions to avoid contact with any areas where the bloom is obviously concentrated at the lake surface or around the shoreline. Alert Level 3 occurs at 15,000 cells ml^{-1}, and at this point lake users are warned to avoid contact with lake water. While levels around 15,000 cells ml^{-1} have a low probability of causing short-term adverse health outcomes (e.g., skin irritation and gastrointestinal illness), the buoyant nature of these algae is such that cells can become concentrated at the lake surface or along the shoreline causing cell density to increase >1000 fold (Chorus and Bartram 1999). Such areas could provide a lethal dose of anatoxin-a to domestic animals and humans. When cell density is >100,000 cells ml^{-1} or surface accumulations (scums) are evident, all lake uses should be curtailed. Due to the patchy nature of blue-green algal

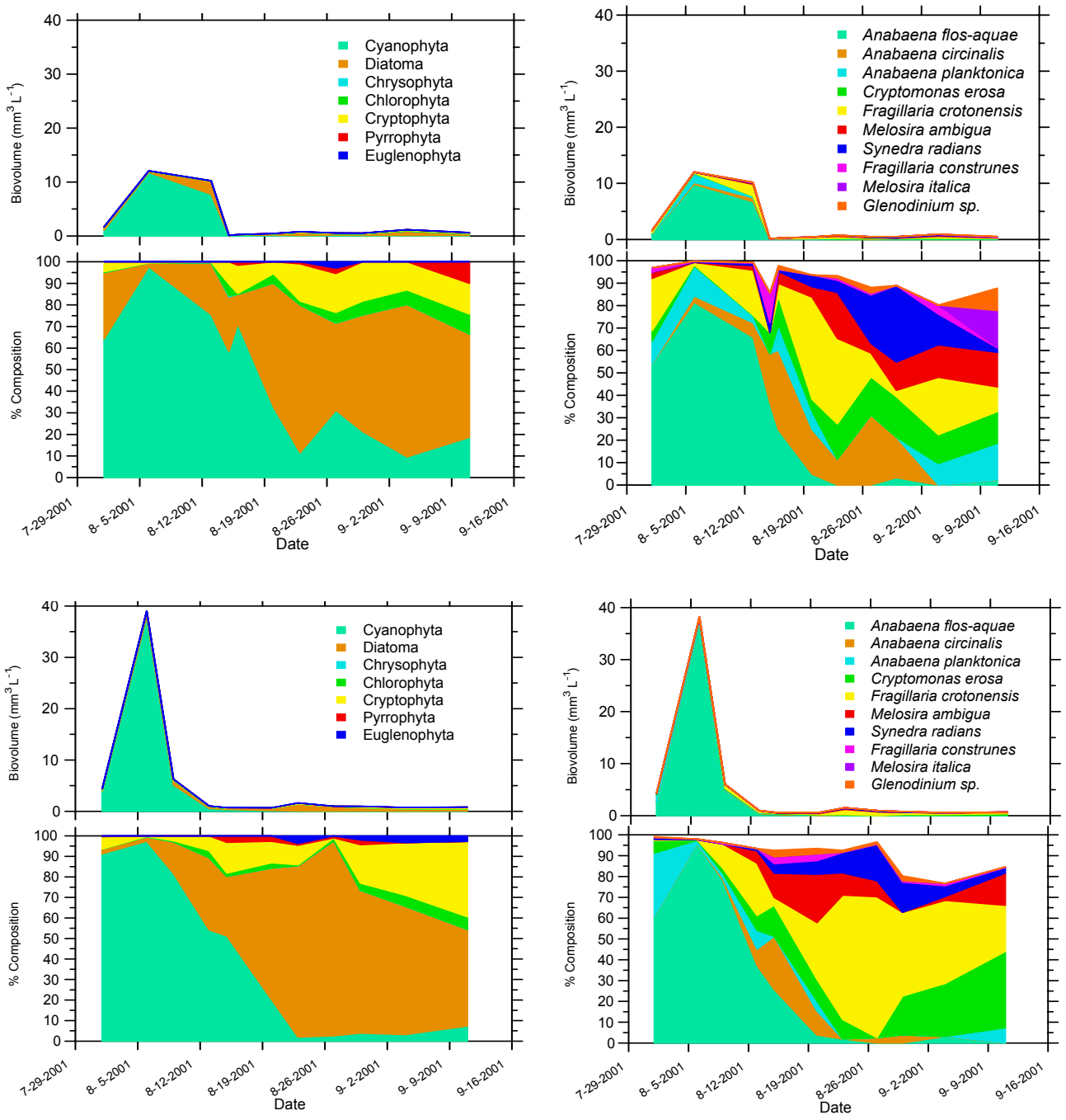

Figure 26. Phytoplankton biomass and percent composition of major taxa (a, c) and individual species (b, d) at North and South Boat Dock sample stations (DND and DSR), Diamond Lake, 2001. Where a = top left; b = top right; c = bottom left; d = bottom right.

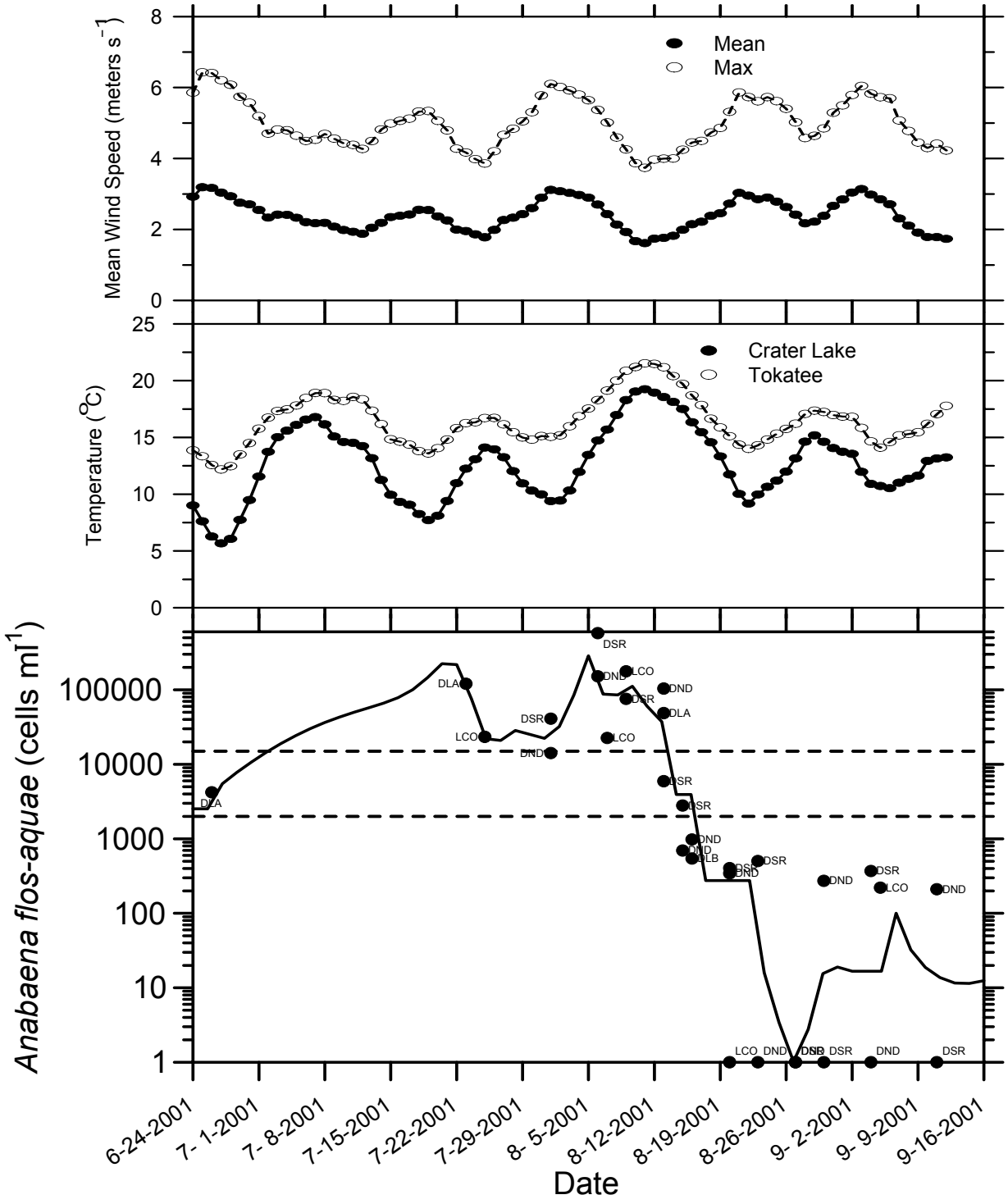

Figure 27. *Anabaena flos-aquae* cell density in Diamond Lake and climatic conditions in the vicinity of Diamond Lake, 2001. Seven day running-mean wind speed at Crater Lake (a, top), seven day running-mean air temperature at Crater Lake and Tokatee (b, middle), and *A. flos-aquae* cell density at all sampling locations (see symbol labels) with fitted distance-weighted-least-squares trend line (c, bottom).

blooms it is possible for higher *Afa* densities (and therefore higher anatoxin concentrations) to be present in areas not sampled in a given survey.

Now that it has been documented that Diamond Lake contains toxigenic *Afa*, rapid sample analysis and reporting is necessary to allow decisions to be made regarding increased spatial and temporal sampling and potential lake closures. It is evident that cell density exceeded Alert Level 2 on the June 26th sample date, yet a significant gap existed prior to additional sampling in late July (Figure 26c). *Afa* cell density for all sample locations and dates from late July through mid August exceeded the Alert Level 3 guideline.

(iii) *Afa Trend Relative to Climatic Factors*

Growth of blue-green algae (Cyanobacteria) such as *Afa* tends to be favored by warmer and calmer in-lake conditions (Reynolds 1984). Climatic data from Crater Lake and Tokatee RAWS site indicate that an extended period of high temperature and low wind occurred from late June through mid July, a period for which no *Afa* data were available (Figure 27a,b). At the time of the July 23rd sample date air temperature was increasing and wind speed decreasing slightly from the previous ~10 day period (Figure 27a,b). As noted above with biovolume, *Afa* decreased in density (although levels still remained above Alert Level 3) following the July 23rd sample date, increased during the first two weeks in August, and then decreased again through August and into September (Figure 27c). This pattern tended to follow both wind and temperature, with a sequence of cooler/windier → warmer/calmer → cooler/windier occurring through the late July to late August period of algal decline, rebound, and decline (Figure 27a,b,c). Lake temperature and stability (as indicated by dissolved oxygen profiles) trends also tended to follow this same pattern (Figures 7 and 12). The increased prevalence of large diatoms (which favor a more mixed condition due to their tendency to sink in the water column reducing access to light) during the August 1st sample date, decrease during the subsequent two weeks, and increase beginning in mid August (Figure 26) is further evidence for the importance of wind and water column stability in dictating species dominance.

Based on the apparent coincidence of climatic and *Afa* trends it is probable that during the late June to mid July period when wind speed was relatively low and air temperatures high, that the algal bloom could well have been equal to or larger than the early August peak. This is consistent with early July Secchi measurements showing a rapid decrease in water clarity (Figure 13) and a verbal report from ODFW staff of bloom conditions evident over the July 4th holiday (D. Loomis, field notes).

(iv) *Toxin Analysis*

Afa has been associated with two toxins: primarily with the neurotoxin, anatoxin-a, and secondarily with the hepatotoxin, microcystin (Chorus and Bartram 1999). Initial

samples (beginning August 6th) were analyzed for both toxins; however, results indicated that microcystin was at very low levels and analysis for this toxin was discontinued after the August 21st sample date (Table 3). Anatoxin-a was at substantial concentrations by the time of the August 6th sample date with variable but substantial concentrations continuing until about August 16th (Table 3). Concentrations then declined until a non-detect was measured on the August 30th sample. Maximum concentrations encountered probably posed minimal risk to humans or animals in terms of acute lethality. However, these values can increase >100 fold in areas where algal cells accumulate along shorelines or at the lake surface. Such areas would pose an acute lethal risk to animals (pets) and humans (Carmichael 2001). As stated above, distribution can be patchy, and not all areas of a lake can be sampled in a given survey.

Table 3. Results of Diamond Lake algal toxin analyses performed at Wright State University using enzyme linked immunosorbent assay (ELISA) for microcystin toxin and liquid chromatography/mass spectroscopy (LC/MS) methodology for anatoxin-a.

					Microcystin Toxin Ananalysis				Anatoxin-a Toxin Results		
Shipment	Date Received	Sample Loction	Date Sampled	Time Collected	Sample Volume	Sample Dry Wt. (g)	Sample Concentration (ug/L)	Sample Concentration +/-Std (ug/L)	Sample Dry Wt. (g)	Sample Concentration (ug/L)	Sample Concentration (ug/g)
1	7-Aug-01	North Shore, Resort Docks	06-Aug-01	1000	1	0.075	0.012	0.0008	75	47.438	0.6325
1	7-Aug-01	South Shore, Boat Ramp	06-Aug-01	1030	1	0.103	0.0019	0.00026	103	240.3045	2.333
2	10-Aug-01	South Shore	09-Aug-01	1038	1	0.045	0.0006	0.00023	44.7	10.423	0.233
2	10-Aug-01	Lake Creek Outlet	09-Aug-01	1100	1	0.082	0.0019	0.00072	81.9	53.741	0.656
3	14-Aug-01	Deepest Point	13-Aug-01	1000	1	0.145	0.021	0.003	144.7	293.807	2.03
3	14-Aug-01	South End	13-Aug-01	1045	1	0.094	0.012	0.0017	93.6	40.369	0.431
4	17-Aug-01	South End, Plankton tow	16-Aug-01	915	1	0.082	0.0025	0.00029	82.1	309.814	3.774
4	17-Aug-01	North End, Plankton tow	16-Aug-01	1000	1	0.094	0.0034	0.00027	66.5	126.004	1.895
5	21-Aug-01	South Shore	20-Aug-01	1020	1	0.054	0.0024	0.00045	54.4	23.614	0.434
5	21-Aug-01	North Boat Dock	20-Aug-01	1040	1	0.048	0.0006	0.00014	48.3	10.701	0.222
6	24-Aug-01	South Dock, Surface grab	23-Aug-01	945					52.8	ND	ND
6	24-Aug-01	North Dock, Surface grab	23-Aug-01	1000					47.6	28.341	0.595
7	28-Aug-01	North Dock, Surface grab	27-Aug-01	1045					42.6	35.31	0.829
7	28-Aug-01	South Dock, Surface grab	27-Aug-01	1030					45.9	29.759	0.648
8	31-Aug-01	North Dock, Surface grab	30-Aug-01						50.9	ND	ND
8	31-Aug-01	South Dock, Surface grab	30-Aug-01						31.3	ND	ND

Anatoxin-a concentration did not always correlate well to *Afa* density (Figure 28a,b). However, the mid August decline in *Afa* density did coincide with a decline in anatoxin-a at the stations in the northern region of the lake (Figure 28a). A substantial anatoxin peak occurred at the southern station well after *Afa* declined to low levels (Figure 28b). Lack of correlation between cell counts and anatoxin is likely the result of variable toxin production during the course of the bloom, as well as the potential for toxin to be released to the water column subsequent to algal cell death and lysing.

(v) *Timeline of Events*

Once the toxic bloom was identified, increased sampling was initiated and appropriate warnings and closures were issued based upon cell density and toxin analyses described above (Figure 29). Again, now that it has been established that toxic blooms can occur in

Diamond Lake, the sampling gap that occurred late June to mid-July can be avoided as regular sampling procedures are followed.

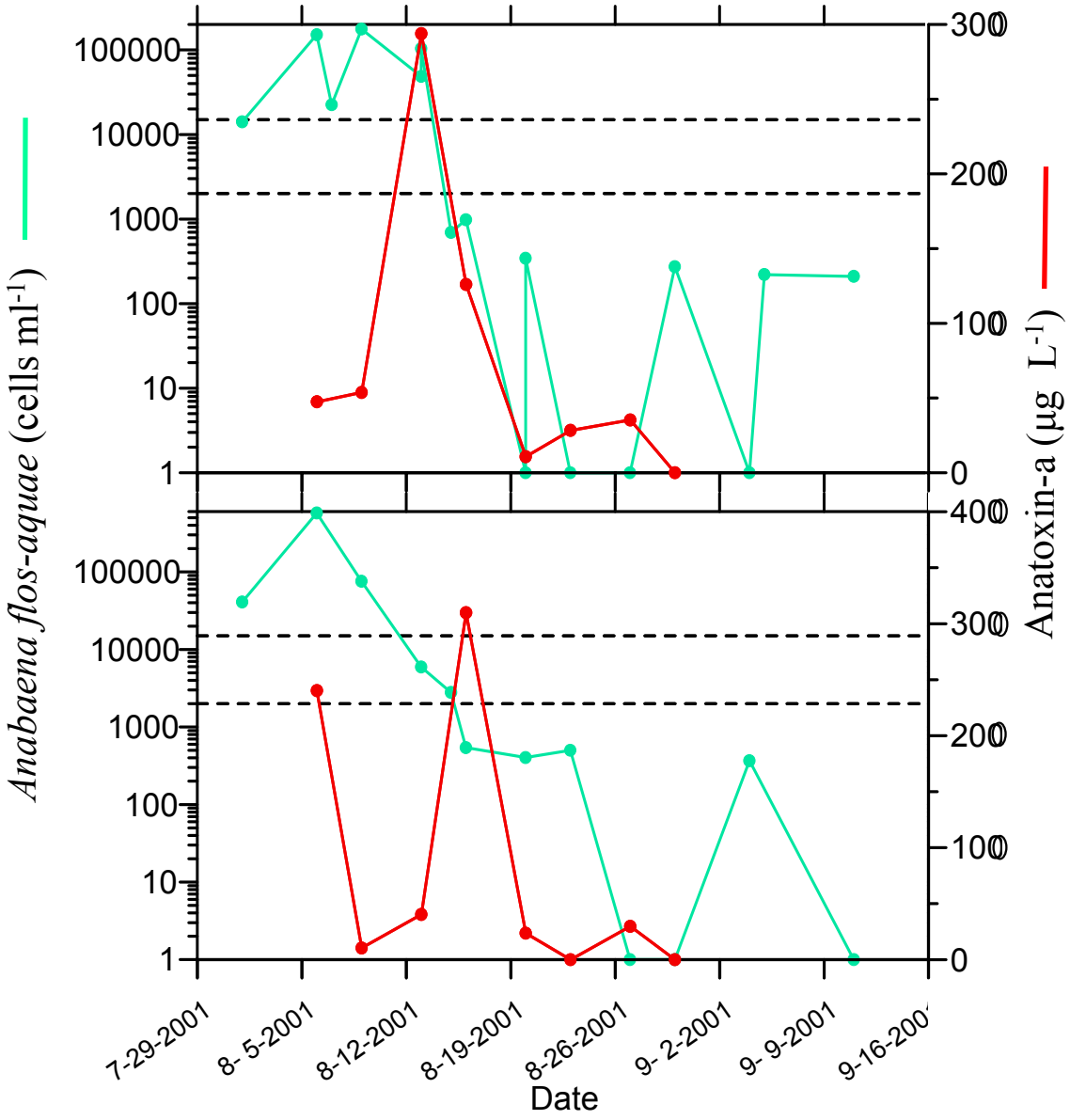

Figure 28. *Anabaena flos-aquae* cell density and anatoxin-a concentration in northern (a, top) and southern (b, bottom) regions of Diamond Lake, 2001. Note: cell density was derived by dividing total *Anabaena f-a* biovolume in cubic

micrometers per ml by the volume of an individual cell {=65 cubic micrometers})

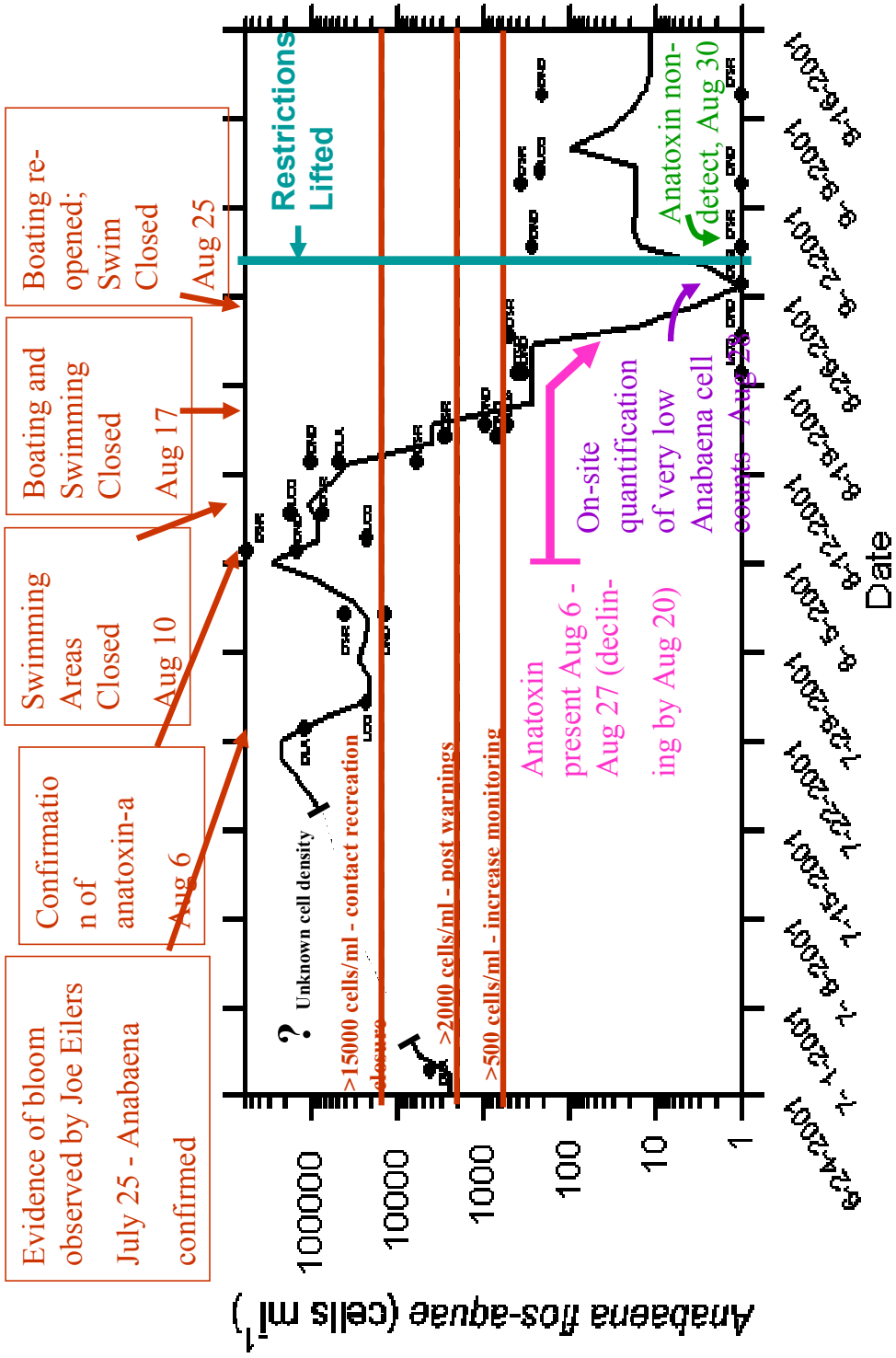

Figure 29. Timeline of events in Diamond Lake, summer 2001.

IMPLICATIONS FOR MONITORING ACTIVITIES

The monitoring results for 2001 were extraordinarily useful in documenting a severe water quality problem in Diamond Lake. The lake experienced a very severe bloom of *Anabaena flos-aquae* that contributed to severe water quality problems with respect to elevated pH, depleted dissolved oxygen, and concentrations of anatoxin-*a* which posed a potential human health threat. There were some atypical weather conditions that may have contributed to this being a singular event including a drought and some very calm conditions that favored dominance of cyanobacteria. However, there are some biological transformations in the lake that have occurred over the last decade that may have contributed to the events of 2001. The formerly successful trout fishery has been replaced by Tui chub leading to the loss of all large cladocerans. The dominant group of zooplankton in Diamond Lake is now rotifers, which have little capacity to graze on larger phytoplankton.

Thus, it is unclear whether the events of 2001 will be repeated on a regular basis or whether this was an anomaly created by a convergence of conditions favorable for cyanobacteria. Regardless, there is increasing pressure to more effectively manage the lake to optimize for a desirable fishery and to minimize the chances for repeat closures of the lake as a consequence of toxic cyanobacteria. Given the uncertainties in what may occur either "naturally" or as a consequence of future changes in fisheries management, there is a need for high quality water quality monitoring to aid in the management decisions. The review of the data from 2001 presented earlier in the report points to a number of changes that could be made to refine the monitoring efforts. This portion of the report offers some suggestions for how to improve the current efforts.

A. Quality Assurance

In the process of assembling the data presented here, there were a number of issues relative to quality assurance that were identified including data collection, sampling tracking, field data documentation, laboratory reporting, and data management.

The field profile data collected by the UNF contractor, RCC, needs to be standardized according to manufacturer's specifications for the instruments being used. The Hydrolab® multi-parameter sonde needs to be held in a stable position for up to two minutes at a given depth while the various probes equilibrate. All of the past data collected have been done by lowering the probe at a slow, but continuous rate causing hysteresis problems illustrated in Figure 5. Continuous checking of the probes also needs to take place in the field so that spurious data are identified and corrected where possible. For example, pH values measured well above 8 in the hypolimnion (Figure 6) should stimulate questions regarding operation of the equipment knowing that the low DO (Figure 12) and low redox (Figure 10) conditions favor low pH rather than high pH.

The data collection conducted by the UNF and its contractor needs to be more formalized to include regular field notes (UNF) and chain-of-custody forms (UNF and RCC) to track the disposition of samples. There was considerable confusion created by where samples

collected for the toxin analysis were actually taken. The use of a GPS in routine sample collection, with the site recorded in a water-proof field notebook, would resolve these questions. In addition, some analyses were run on the wrong aliquots. In the future, both TP and NH_3 should be run on the unfiltered aliquots. The laboratories should be encouraged to report data in standard units. For example, the analyses labeled "TN" were actually "TKN". Alkalinity is being reported as HCO_3 as mg/L carbon, rather than the more typical HCO_3 or $CaCO_3$. Failure to catch these subtle distinctions can result in major errors in reporting the results.

The use of quality assurance (QA) samples varied widely among the investigators. Whereas DEQ employed QA samples including duplicates, blanks, and audit (reference) samples on each site visit, we could find no record of quality assurance samples submitted by RCC to the USFS laboratory in 2001. If this is a budgetary issue, the UNF needs to provide sufficient funds in the sampling program to include adequate QA support. These samples should not be viewed as optional.

In addition, all parties involved in sample collection used their own codes or descriptions for site designation. Use of a standardized site code would help to minimize confusion in future years as multiple organizations collect data. Also, investigators should be encouraged to use the metric system in reporting results. The data were assembled from a number of laboratories and investigators, each using their own file types and format structures. The UNF has the capability to request that all data be supplied electronically and in a specified format. This would minimize errors in data transmission and assembly.

As noted earlier, most of the literature related to cyanobacterial toxicity has reported phytoplankton results in terms of cells per volume (mL). Following this practice would facilitate the task of interpreting the phytoplankton and toxicity results for future activities.

(B) Sample Coordination

To its credit, the UNF has seen the value of developing a longer-term data record for Diamond Lake and has contracted sample collection on the lake and tributaries since 1992. However, the water quality problems have reached the point where it is likely that a more formal monitoring and research effort will be required to better understand the conditions and processes in the lake. In addition, the serious nature of potential human health threats associated with toxic cyanobacteria blooms require better communication among affected parties. The unusual conditions in Diamond Lake were noted by a number of individuals and ODFW staff notified DEQ staff on July 11 that serious bloom conditions existed on the lake. The UNF contractor indicated in the field notes the bloom conditions on the routine sampling conducted on July 23. However, it wasn't until July 27 that the hydrologist at the UNF was notified by another private contractor not connected with the project that bloom conditions existed and it was caused by *Anabaena flos-aquae*. At that point, the UNF acted rapidly to monitor the problem and take action to protect the public, but it is likely that the peak bloom conditions had already passed by the time the first toxin samples had been collected.

A more rapid-response program needs to be employed on Diamond Lake to provide some warning of changing conditions. One approach would be to locate an on-site cooperator to measure Secchi disk transparency frequently and report the results to the UNF. Another choice would be to use on-site agency personnel to perform the tasks. ODFW may have staff available to provide frequent updates on the condition of the lake. A review of the 2001 data shows that the transparency was decreasing rapidly as early as mid-June, which in hindsight foreshadowed the developing bloom. A decline in transparency to a threshold level (eg. 2 m) could be used to trigger the collection of a phytoplankton sample for analysis of phytoplankton community composition or at least conduct a screening for relative abundance of cyanobacteria taxa.

There is an opportunity to work among the agencies to better coordinate data collection and integration on Diamond Lake. For example, both ODFW and DEQ were aware of serious bloom conditions on the lake in 2001 at least two weeks before UNF was informed. Had UNF been informed, they could have instructed its contractor to alter the planned schedule to sample earlier. ODFW is at the lake often to conduct fisheries monitoring activities, but for a modest level of additional effort some valuable limnological data could be collected as well. Within the UNF, there is also room for improved coordination of tasks. For example, the UNF maintains two RAWS climate stations that exist to inform the fire program of local weather conditions. However, by upgrading the sites, valuable long-term climatic data could be made available for documenting weather conditions at Diamond Lake. Alternatively, a weather station operated by facilities management at the Diamond Lake treatment lagoons could be upgraded to serve dual purposes.

(C) Monitoring Design

Future monitoring for toxic blooms should begin in late May at the DLA station and continue bi-weekly thereafter. If cell density of *Afa* (or other known toxigenic species) exceeds 500 cells ml^{-1}, then DLA and a series of shoreline stations should be sampled on a weekly basis (Figure 30). If cell density exceeds 15,000 cells ml^{-1} samples should be analyzed for toxin concentration on a biweekly basis. Sampling should continue until cell density drops below 500 cells ml^{-1}.

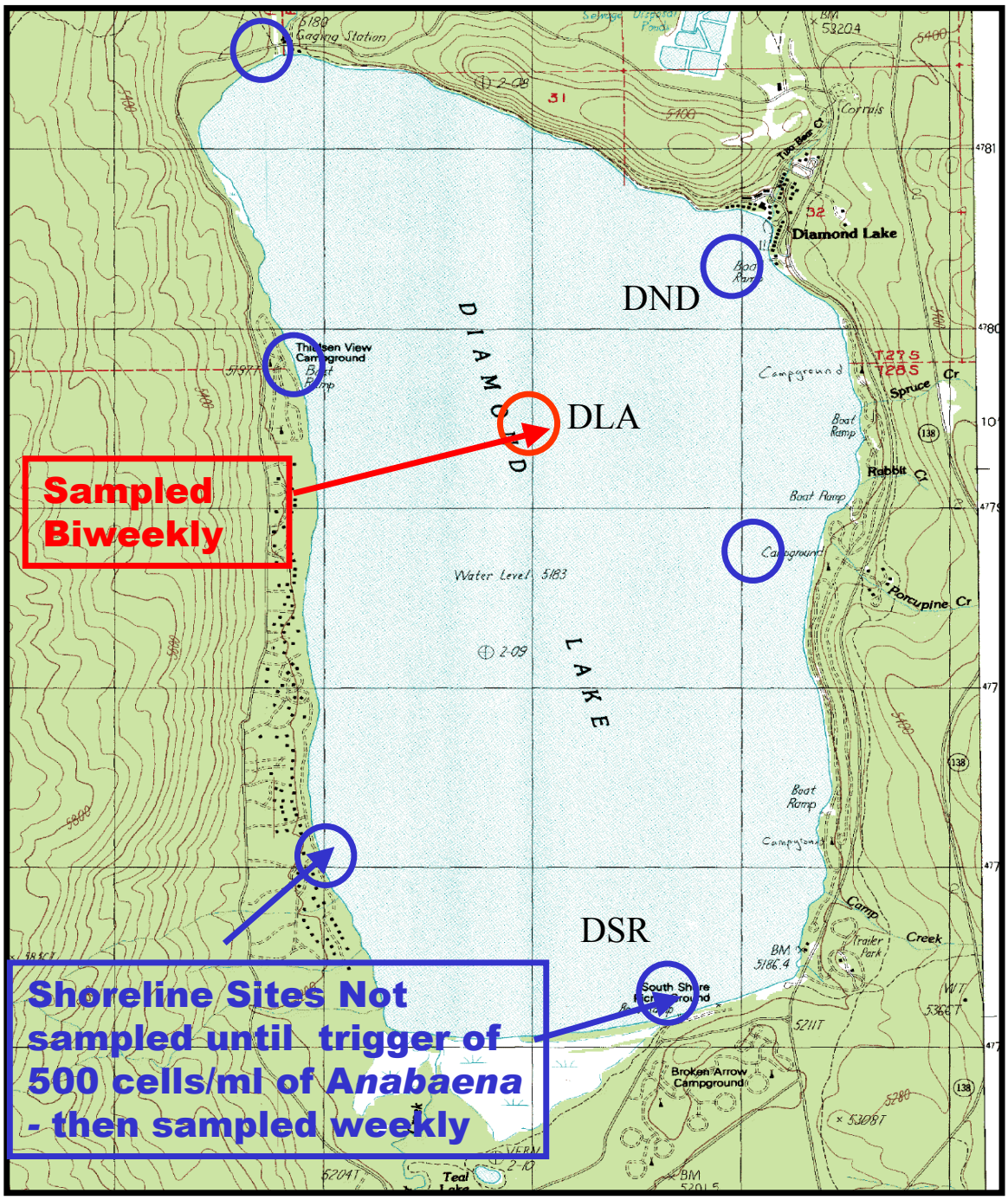

Figure 30. Sample site and frequency recommendations for toxic bloom monitoring in Diamond Lake.

Diamond Lake was sampled extensively during the summer of 2001. Part of the sampling by the UNF was planned, part of it was fortuitous (DEQ and the TMDL sampling; the PacifiCorp Lemolo Lake study), and part was conducted in response to the cyanobacteria bloom. Much of the information was very useful in helping to document conditions on the lake. However, the current activities only serve to monitor the events without developing an understanding of the processes that cause the events. Without a designed research program directed at answering specific questions, it is likely that problems will continue at Diamond Lake. The research effort needs to consider developing an information base on fundamental processes in the lake that would include, but not be limited to, climate, hydrology, sediment interaction, and trophic disruption processes related to the fisheries-zooplankton-phytoplankton interactions. A first step in developing the research design is to compile the historical data on the lake into a comprehensive database, perhaps one based on the database presented in this report. The review of the historical data would probably answer some questions regarding how the lake has responded, while serving to better formulate testable hypotheses for future research efforts.

REFERENCES

Carmichael, W. W. 2001. Diamond Lake toxin analysis report. Provided to Umpqua National Forest, Roseburg, Oregon. Wright State University, Department of Biological Sciences, Dayton Ohio. 7 p.

Chorus, I. and J. Bartram. 1999. Toxic Cyanobacteria in Water; A Guide to their Public Health Consequences, Monitoring and Management. World Health Organization Report. E & F Spon, London and New York. 416 p.

Eilers, J.M., C.P. Gubala, P.R. Sweets, and D. Hanson. 2001. Effects of fisheries management and lakeshore development on water quality in Diamond Lake, Oregon. *J. Lake and Reservoir Mgmt.* 17:29-47.

Eilers, J.M., J. Beaver, A. St. Amand, and J. Cornett. 2001. Historical changes of zooplankton and cyanobacteria in Diamond Lake, Oregon based on analysis of the sediment record. Report to the Oregon Department of Fish & Wildlife, Roseburg, Oregon.

Kann, J. 2001. On-site quantification of *Anabaena* during a toxic algal bloom in diamond Lake, August 28th, 2001. Brief Technical Memo provided to Umpqua National Forest, Roseburg, Oregon. 5p.

Reynolds, C. S. 1984. Phytoplankton Ecology. Cambridge University Press, London. 384 p.

Yoo, S.R., W.W. Carmichael, R.C. Hoehn, and S.E. Hrudy. 1995. Cyanobacterial (blue-green algal) toxins: a resource guide. AWWA Research Foundation and American Water Works Association. Denver, CO. 229 p. (ISBN 0-89867-824-2)

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